Contemporary Environmental Readings
Volume 1

Climate Change
A Blessing or a Curse for Agriculture?

First Edition

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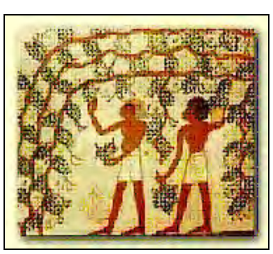
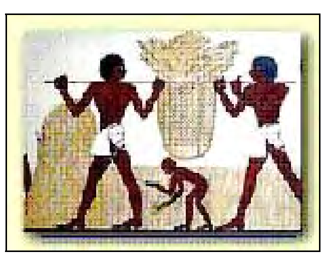
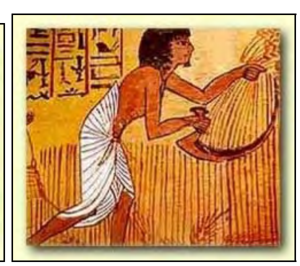
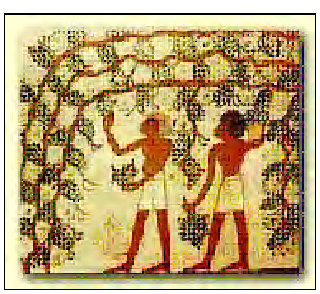
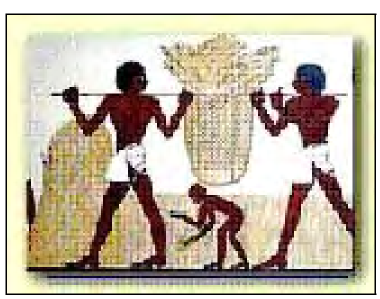
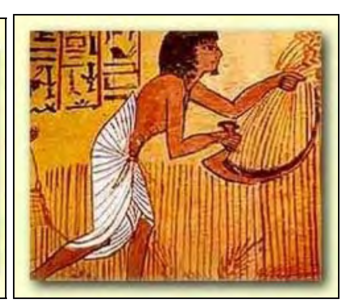
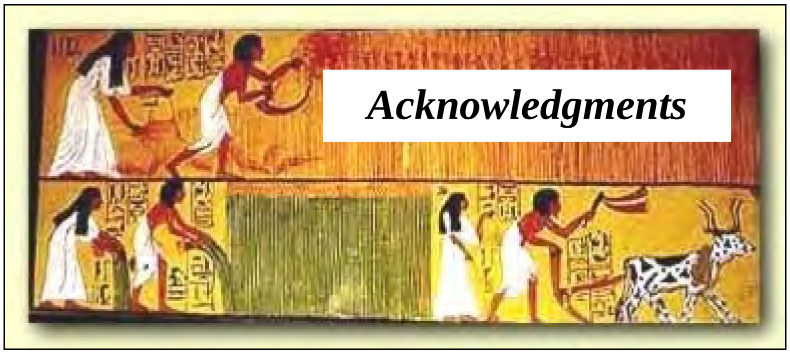




Dedication

To
Our
Families



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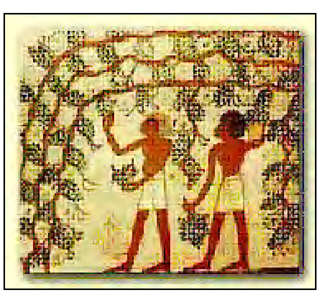

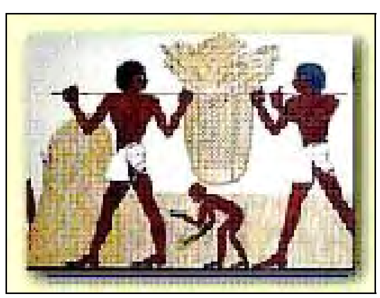

Climate change: a blessing or a curse for agriculture?

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1 *Climate Change and Agroecosystem*

"ظَهَرَ الْفَسَادُ فِي الْبَرِّ وَالْبَحْرِ بِمَا كَسَبَتْ أَيْدِي النَّاسِ لِيُذِيقَهُمْ بَعْضَ الَّذِي عَمِلُوا لَعَلَّهُمْ يَرْجِعُونَ" الروم الآية 41

"Corruption has appeared throughout the land and sea by [reason of] what the hands of people have earned so He may let them taste part of [the consequence of] what they have done that perhaps they will return [to righteousness]"

(***Holy Quran***: Ar-Room, verse 41)

Key terms

Carbon sink: A reservoir that removes carbon dioxide from the atmosphere and provides storage over a period of time; the reservoir can be a natural sink, for example trees and oceans absorb vast quantities of carbon dioxide, or a man-made one, such as carbon capture and storage schemes.

Climate: The average weather, encompassing natural variability and extremes.

Greenhouse gas: A gas that contributes to trapping heat in the atmosphere, warming the Earth, including carbon dioxide, methane and water vapor; they are both naturally occurring and also released into the atmosphere by humankind.

Global warming: The rise in global temperature observed during the 20th century and projected to continue into the future, caused by human beings' increased emissions of greenhouse gases.

Climate change: The changes in the observed and projected climate around the world; a natural phenomenon altered due to human beings' activities; a more comprehensive term than global warming as it also includes changes to rainfall, ocean and atmosphere circulation patterns and sea level.

Adaptation: Taking action to minimize the current and expected impacts of climate change.

Mitigation: Taking action to reduce greenhouse gas emissions and enhancing natural and artificial processes that remove greenhouse gases from the atmosphere.

Global warming potential (GWP): A term indicating how much a greenhouse gas contributes to global warming when compared to the same amount of carbon dioxide over a set period of time (often 100 years); for example, the GWP of methane over 100 years is 23, meaning that 23 tonnes of CO_2 would need to be emitted to cause the same effect as 1 tonne of methane.

IPCC AR4: Intergovernmental Panel on Climate Change Assessment Report 4; the IPCC is a scientific intergovernmental body set up by the World Meteorological Organization and the United Nations Environment Programme to provide decision-makers and others with an objective source of information about climate change.

Kyoto Protocol: An addition to the UNFCCC, providing legally binding measures to reduce greenhouse gas emissions; the gases or groups of gases covered by the Kyoto Protocol are carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, hydrofluorocarbons and perfluorocarbons; by December 2008 it had been ratified by 183 parties.

Food security: Food security refers to the availability of food and one's access to it; a household is considered food secure when its occupants do not live in hunger or fear of starvation.

Vector-borne disease: A vector-borne disease is one in which pathogens such as viruses or bacteria are transmitted from an infected individual to another by arthropods such as mosquitoes and ticks, usually through a bite; sometimes other animals serve as intermediary hosts.

1.1 *Why the Interest in Global Climate Change?*

1.1.1 *Introduction*

The world population is projected to increase from about 7 billion in 2011 to 9.2 billion in 2050. The current rate of increase is about 6 million per month, with almost all growth occurring in developing countries where natural resources are already under great stress. The Green Revolution technology led to the doubling of food production between 1950 and 2010, with only a 10% increase in the area under production (***FAO, 2010***). However, meeting the food demand of the growing population, rising standards of living, and changes in diet preferences will necessitate an additional 70% increase in production between 2010 and 2050 (***Burney et al. 2010***). Grain yields of wheat (***Semenov, 2009***) and rice (***Wassmann et al. 2009***) are sensitive to high temperatures. The problem of food insecurity is also exacerbated by increases in the severity and extent of soil degradation. This is especially true because of declines in the soil structure and hydrological properties in conjunction with reductions in the quantity and quality of soil organic carbon (SOC) content caused by a widespread use of extractive farming practices (i.e., indiscriminate residue removal, excessive grazing, the use of animal dung as household fuel rather than as manure, and a negative nutrient budget). Over and above the biophysical constraints being exacerbated by a changing climate and an increase in the frequency of extreme events, there are also issues related to the human dimensions. To the resource-poor and small-size land holders of the tropics and subtropics, neither the essential inputs are available (e.g., improved seeds and fertilizers and new equipment such as no-till seed drills and soil testing facilities), nor affordable. One, these inputs are prohibitively expensive. Two, farmers are not sure about their effectiveness, especially under conditions of uncertain rains, frequent droughts, and a high incidence of weeds and other pests (***Lal and Stewart, 2012***).

Climate change is a natural phenomenon, but humankind has drastically altered the process. When we use computers to model only the natural influences on the climate, we cannot explain the rapid rise in global temperatures we have seen during the 20th century. It is only when we include the influence of our emissions of greenhouse gases into the atmosphere over the last 150 years that we can replicate the temperature rises seen in recent decades. To help to avoid unacceptably dangerous climate change in the future, many countries and regions have set targets for reducing their greenhouse gas emissions.

According to the **IPCC (2008)**, climate change is any "*change in climate over time whether due to natural variability or as a result of human activity*". It is general consensus among IPCC researchers that increases in atmospheric concentrations of greenhouse gasses (mainly CO_2, CH_4, N_2O and O_3) since pre-industrial times have led to a warming of the surface of the earth. During the last

250 years, the atmospheric concentrations of CO_2, CH_4 and N_2O have increased by 30%, 145% and 15%, respectively. The emissions are mainly due to the use of fossil fuels, but changes of land use as well as agriculture are also major sources of emissions (***Raberg, 2008***).

Climate change caused by the progressive anthropogenic emissions of greenhouse gases is already affecting natural and human systems and sectors throughout the world and the changes to date may be only inklings of profound changes to come. Some contend that action on climate change should be delayed because of the uncertainties surrounding the exact nature, extent, and rate of the portending changes. Others believe that responding to climate change is now necessary precisely because of the uncertainties. In any case, the prospect of significant changes in agroecosystems requires us to anticipate the potential impacts of climate change, to study how farming regions and systems can adjust to those that are unavoidable, and to determine how they can mitigate climate change so as to reduce its ultimate effects (***Hillel and Rosenzweig, 2011***).

The climate scenarios of the IPCC are based on socio-economical scenarios. The scenarios represent different paths of demographical, social, economical and technical development for the main factors that emit climate gasses. Four main scenarios of development have been described as A1, A2, B1 and B2 (**Figure 1.1**). An important difference between the main scenarios is the grade of globalization, which is assumed to strongly affect the global economical and technical development, with a subsequent effect on emissions. There is an emphasis on economic growth in the A-scenarios while the B-scenarios consider a more sustainable development. There are also many other scenarios that have been modeled and thereby result in quite different future scenarios (***Raberg, 2008***).

From his remarkable book '*Global warming – the complete briefing*' ***Sir J. Houghton (2009)*** in the 4^{th} edition, wrote about the emission scenarios of the Special Report on Emission Scenarios (SRES), which are based on a set of four different storylines within each of which a family of scenarios has been developed – leading to a total of 35 scenarios.4 as follows (**Figure 1.2**):

(1) A1 storyline: The A1 storyline and scenario family describes a future world of very rapid economic growth, a global population that peaks in mid century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups which describe alternative directions of technological change in the energy system. The three groups are distinguished by their technological emphasis: fossil fuel intensive (A1FI), non-fossil fuel energy sources (A1T) or a balance across all sources (A1B) – where balance is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy-supply and end-use technologies.

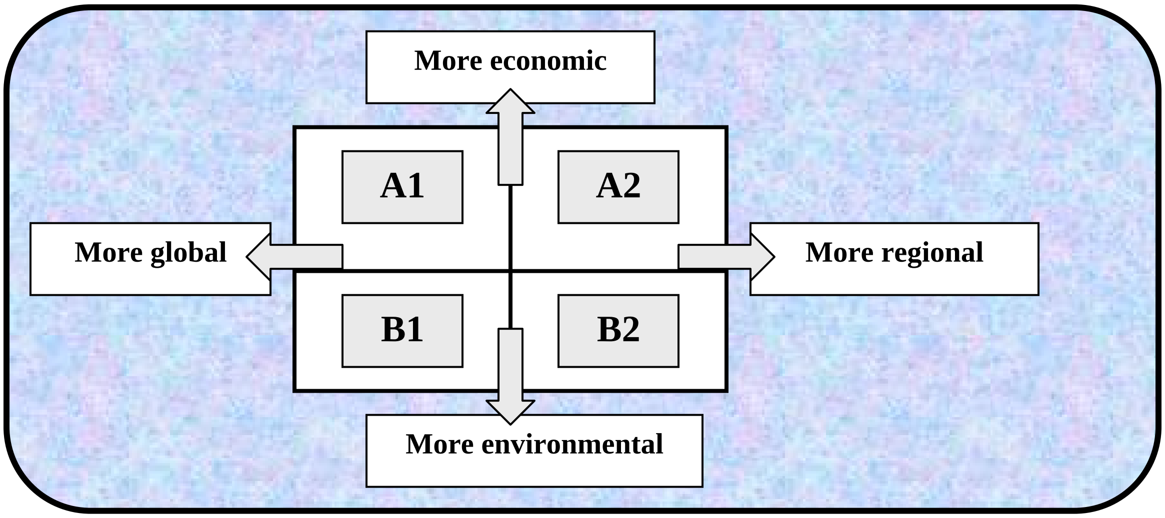


Figure 1.1: The different scenarios are based on diverse development of the global societies (adapted from ***Raberg, 2008*** and from ***IPCC, 2000***).

(2) A2 storyline: The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

(3) B1 storyline: The B1 storyline and scenario family describes a convergent world, with the same global population that peaks in mid century and declines thereafter as in the A1 storyline, but with rapid change in economic structures towards a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate-related initiatives.

(4) B2 storyline: The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with a continuously increasing global population, at a rate lower than in A2, intermediate levels of economic development and less rapid and more diverse technological change than in the B1 and A1 storylines. While the storyline is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

This chapter is especially focused on global climate changes and agroecosystem. This introductory chapter describes some of the agroecosystem-related global climate changes including the following items: agrometeorology agroecosystems and agrobiodiversity, climate changes and agroecosystems and finally, impacts of climate changes on agrobiodiversity.

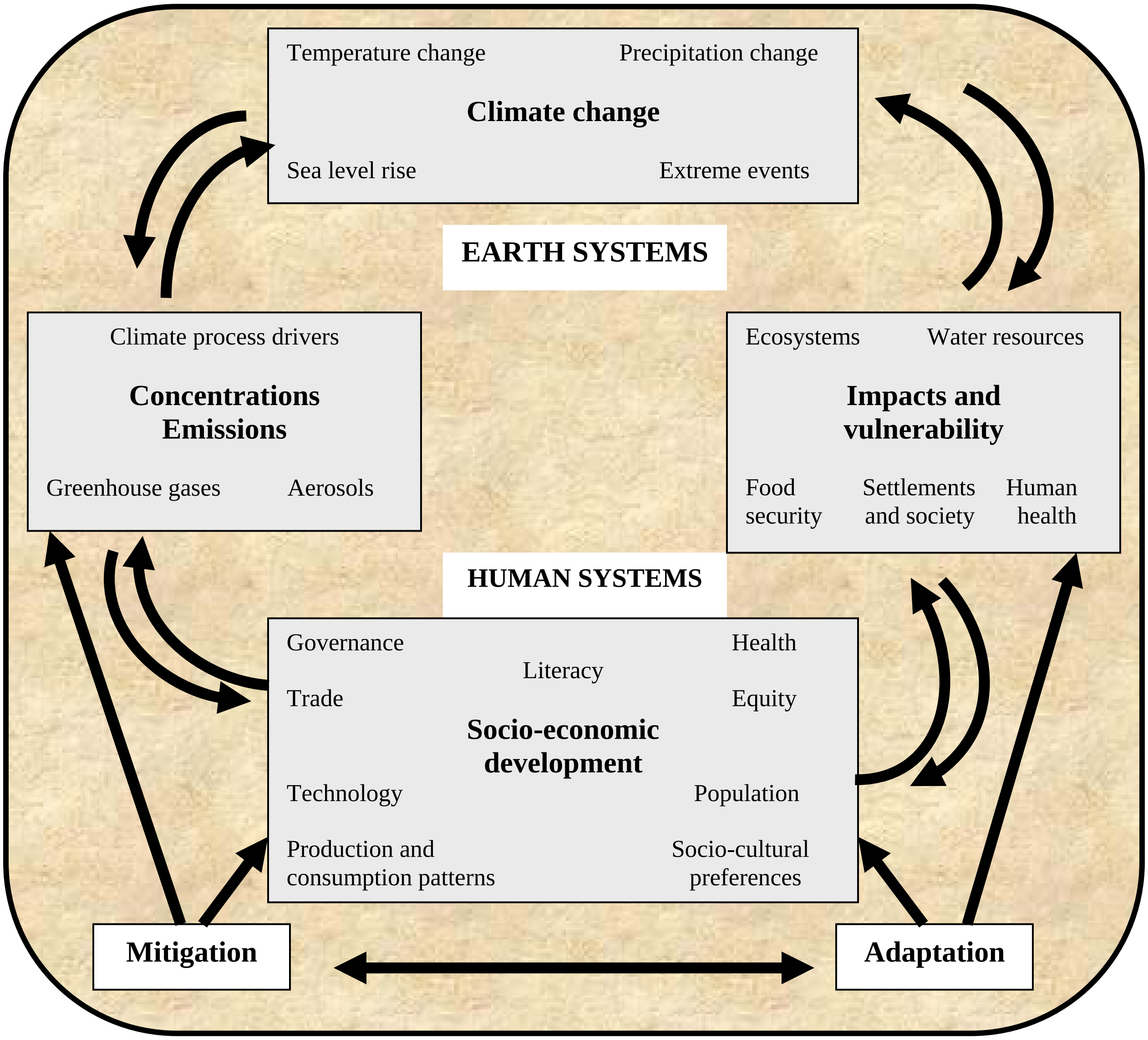


Figure 1.2: Climate change – an integrating framework (adapted from ***Houghton, 2009***)

1.1.2 *Elements of the Climate System*

The atmospheric gases are nitrogen, oxygen, and the trace gases, including the noble gases and the greenhouse gases (water vapor, methane, carbon dioxide, ozone, and nitrous oxide). These greenhouse gases trap some of the energy from the Sun, creating a natural greenhouse effect, without which normal temperatures would be much lower and the Earth would be too cold to live on. Thanks to the greenhouse effect, the Earth's average temperature is 60°F (16°C). Problems begin when the natural greenhouse effect is enhanced by human-generated emissions of greenhouse gases. Scientists now predict that the Earth's climate will change because human activities are altering the chemical composition of the atmosphere through the buildup of greenhouse gases. In order to understand global warming, it is necessary to understand climate (***Casper, 2010***).

***What is the difference between climate and weather*?**

The distinguishing factors between weather and climate are (1) the time interval in which they are taking place (such as a day versus a season) and (2) the scale of the area they are taking place over (such as a village versus a country). Weather is what the atmosphere is currently doing— snowing, raining, or clear skies. Climate is how the atmosphere behaves over relatively long time intervals such as hot summers, cool winters, or wet springs. Climate also refers to the average condition of a region, measured in characteristics such as temperature, amount of rainfall or snowfall, how much snow and ice cover there is on the ground, and the characteristics of the predominant winds; the long-term trends of an area. As an illustration, Hawaii may be described as having a tropical climate, Britain a maritime climate, and Saudi Arabia an arid climate. Climate applies to long-term changes (months, years, and longer); weather the shorter fluctuations that last hours, days, or weeks. The weather may be snowing, raining, clear and sunny, hot, or windy. Weather conditions generally apply only to limited geographical regions and can change rapidly (**Casper, 2010**, in his wonderful book "*Greenhouse gases: worldwide impacts*" from *Global Warming Series* and published with distinguished Publishing House: *Facts on File*).

He noted that when scientists say: "*climate has changed*", they are referring to the fact that the averages of the daily weather have changed over time—such as a region is drier, receiving half as much rain, than it was 50 years ago. There can also be short-term climatic variations, such as those associated with El Niño, La Niña, or volcanic eruptions. Climate affects everyone on Earth in some way, just as global warming will affect everyone on Earth. The weather plays some part in everything humans do, whether it is in transportation, growing food, producing an adequate water supply, or producing and manufacturing goods. Global warming will have an impact on every human on the globe, in varying intensities.

Scientists have determined that rising global temperatures will change precipitation patterns, melt ice caps, raise sea levels, affect water supplies, damage the world's forests, spread disease, cause both floods and droughts, and encourage hazardous weather events. All of the Earth's ecosystems will be affected. Because crop yields, food systems, and water supplies are being jeopardized as the Earth's atmosphere heats up at an accelerated rate, it is critical that scientists study, understand, and unlock the mysteries of global warming now before more damage is done. Technology has advanced to the point that climatologists (scientists who study the climate) have developed several tools that allow them to not only study current climate, but piece together evidence of past climates, and build models to predict future climates.

It is important to understand that even without global warming; the Earth's climate is always fluctuating. Change is natural. The Earth's climate has changed throughout geologic time as the Earth's continents have shifted positions, as the Earth's orbit and the tilt of its axis have changed, and even as the chemical composition of the atmosphere has evolved. The Earth's climate system consists of air, land, water, ice, and vegetation. Climatologists study these components in terms of their cause and effect—also called forcing and response. The term *forcing* describes the things that cause the change; the *responses* are the changes that occur. **Figure 1.3 (a and b)** illustrates the overall climate system along with the interaction of the components within the system. Sometimes climatologists find that the forcings can be cyclic in nature.

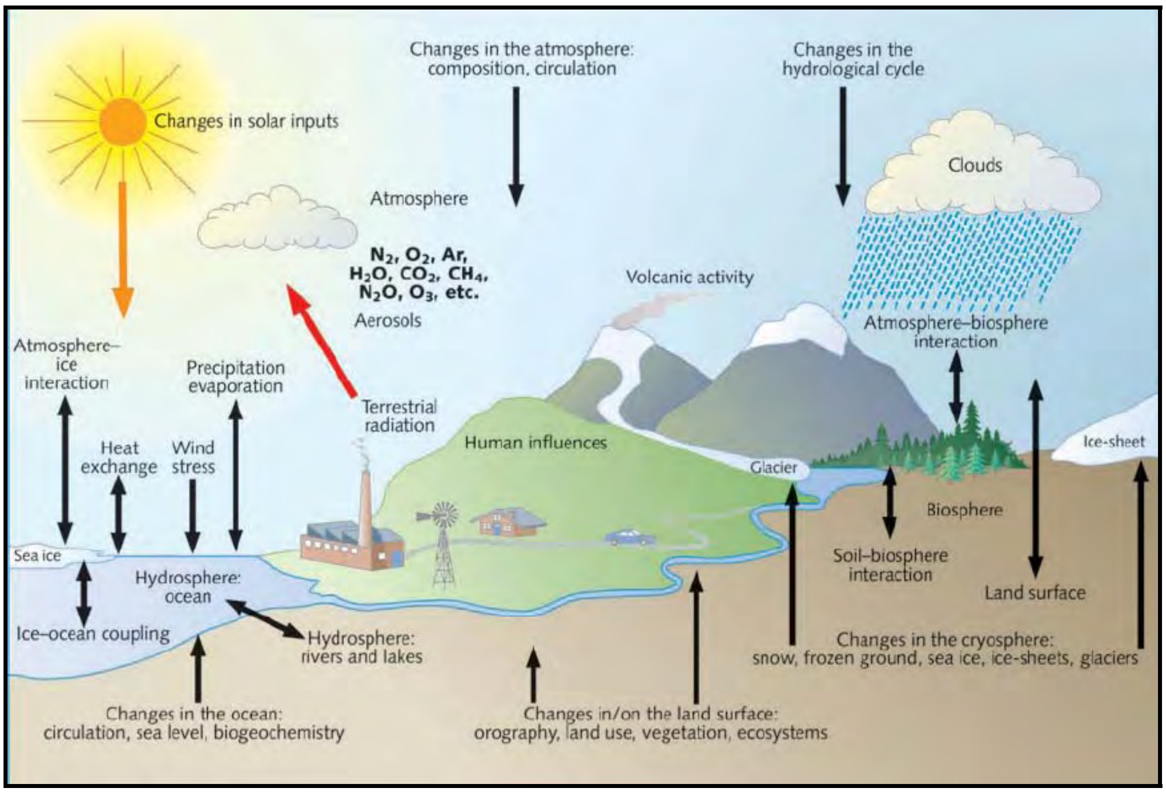


Figure 1.3a: Components of the climate system, their processes and interactions. Changes indicated (bold arrows) are changes in factors that influence the climate system. These include natural factors that affect the climate system such as variations in solar input and volcanic activity. Human influences include change in land use/cover, changes to the atmospheric composition, particularly concentrations of CO_2, CH_4, N_2O and aerosols. Thin arrows indicate interactions between components/processes (from ***Le Treut et al. 2007***).

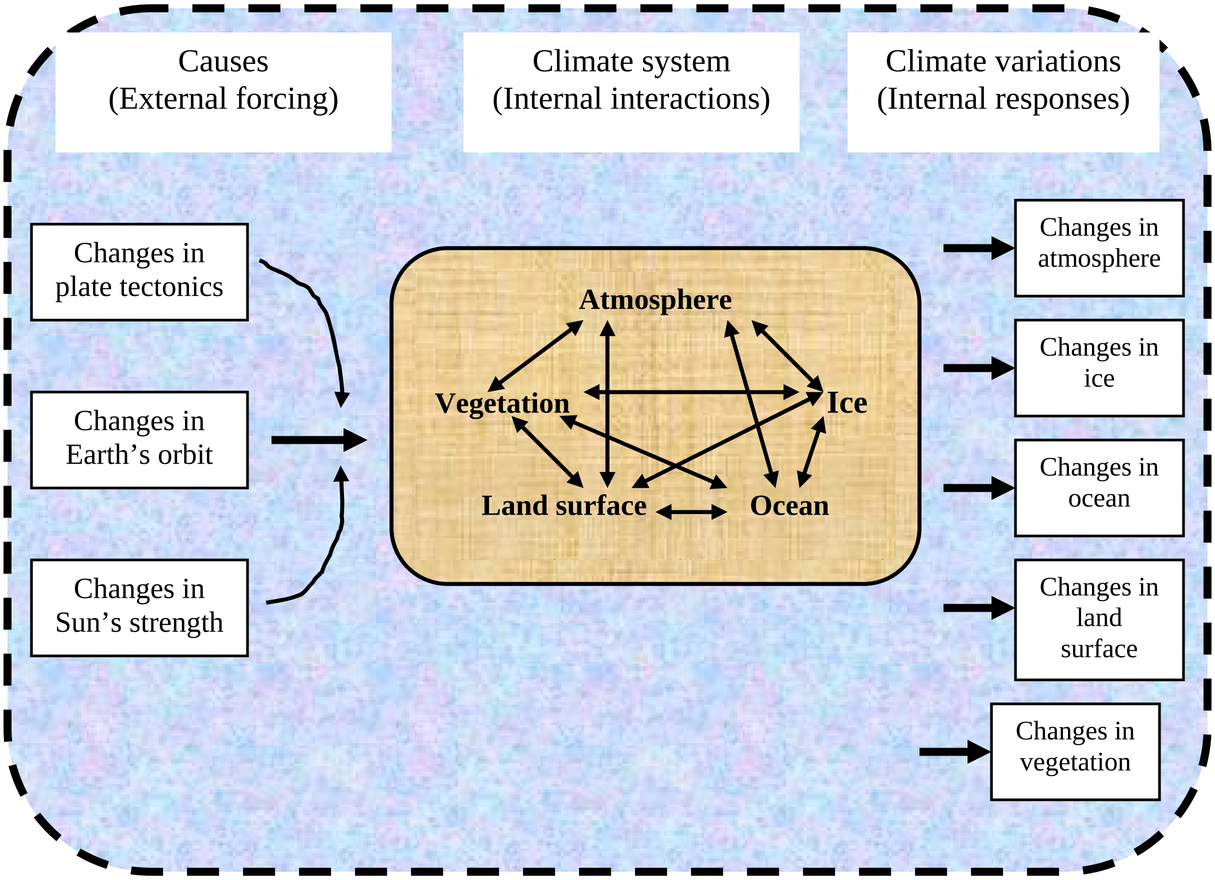


Figure 1.3b: Earth's climate system is composed of many components that all interact. A change in any one component causes changes in others (adapted from ***Casper, 2010***)

1.1.3 *Climate and non-climate drivers of change*

Climate is a key factor determining different characteristics and distributions of natural and managed systems, including the cryosphere, hydrology and water resources, marine and freshwater biological systems, terrestrial biological systems, agriculture and forestry. For example, temperature is known to strongly influence the distribution and abundance patterns of both plants and animals, due to the physiological constraints of each species. Dramatic changes in the distribution of plants and animals during the ice ages illustrate how climate influences the distribution of species. Equivalent effects can be observed in other systems, such as the cryosphere. Hence, changes in temperature due to climate change are expected to be one of the important drivers of change in natural and managed systems (***IPCC, 2007b***).

Many aspects of climate influence various characteristics and distributions of physical and biological systems, including temperature and precipitation, and their variability on all timescales from days to the seasonal cycle to interannual variations. While changes in many different aspects of climate may at least partially drive changes in the systems, we focus on the role of temperature changes. This is because physical and biological responses to changing temperatures are often better understood than responses to other climate parameters, and the anthropogenic signal is easier to detect for temperature than for other parameters. Precipitation has much larger spatial and temporal variability than temperature, and it is therefore more difficult to identify the impact it has on changes in many systems. Mean temperature (including daily maximum and minimum temperature) and the seasonal cycle in temperature over relatively large spatial areas show the clearest signals of change in the observed climate (***IPCC, 2001b***).

The IPCC Working Group II Third Assessment Report (WGII TAR) found evidence that recent regional climate changes, particularly temperature increases, have already affected many physical and biological systems, and also preliminary evidence for effects in human systems (***IPCC, 2001a***). Both climate and non-climate drivers affect systems, making analysis of the role of climate in observed changes challenging. Non-climate drivers such as urbanization and pollution can influence systems directly and indirectly through their effects on climate variables such as albedo and soil-moisture regimes. Socio-economic processes, including land-use change (e.g., forestry to agriculture; agriculture to urban area) and land-cover modification (e.g., ecosystem degradation or restoration) also affect multiple systems. Non-climate drivers, such as land use, land degradation, urbanization and pollution, affect systems directly and indirectly through their effects on climate (**Table 1.3**). These drivers can operate either independently or in association with one another. Complex feedbacks and interactions occur on all scales from local to global (***IPCC, 2007b***).

1.2 *Climate changes and agroecosystems*

1.2.1 *Introduction*

The world faces an increasing demand for its finite resources. There will be 1.7 billion more people to feed by 2030, but with a declining ratio of arable land between 40% and 55% and about 1.8 billion people living under water scarcity (***CropLife International, 2009***). Furthermore, a recent scenario analysis suggests that on average about 3000 kcal per capita daily will need to be available worldwide in 2050 to feed the growing human population (***Hubert et al. 2010***). This goal may be seen as attainable but the world in the mid-21st century will be facing water shortages, flooding and global warming as a result of climate change. Increasingly, more wealthy and healthy people will demand greater dietary diversity in a global bio-based economy. Global economic growth and sustainable intensification of crop–livestock agroecosystems remain therefore as major challenges for feeding this growing human population. In this regard, today's farming worldwide needs high yielding crops that can grow more efficiently, such as those requiring less inputs or adapting to water and heat stresses or new epidemics of emerging pests at a time of global climate change (***Lenné and Wood, 2011***).

Table 1.3: Direct and indirect effects of non-climate drivers (***IPCC, 2007b***)

Non-climate driver	*Examples*	*Direct effects on systems*	*Indirect effects on climate*
Geological processes	Volcanic activity, earthquakes, tsunamis (e.g., ***Adams et al. 2003***)	Lava flow, mudflows (lahars), ash fall, shock waves, coastal erosion, enhanced surface and basal melting of glaciers, rock fall and ice avalanches	Cooling from stratospheric aerosols, change in albedo
Land-use change	Conversion of forest to agriculture (e.g., ***Lepers et al. 2004***)	Declines in wildlife habitat, biodiversity loss, increased soil erosion, nitrification	Change in albedo, lower evapotranspiration, altered water and heat balances (e.g., ***Bennett and Adams, 2004***)
	Urbanization and transportation (e.g., ***Kalnay and Cai, 2003***)	Ecosystem fragmentation, deterioration of air quality, increased runoff and water pollution (e.g., ***Turalioglu et al. 2005***)	Change in albedo, urban heat island, local precipitation reduction, downwind precipitation increase, lower evaporation (e.g., ***Weissflog et al. 2004***)
	Afforestation (e.g., ***Rudel et al. 2005***)	Restoration or establishment of tree cover (e.g., ***Gao et al. 2002***)	Change in albedo, altered water and energy balances, potential carbon sequestration
Land-cover modification	Ecosystem degradation (desertification)	Reduction in ecosystem services, reduction in biomass, biodiversity loss (e.g., ***Nyssen et al. 2004***)	Changes in microclimate (e.g., ***Su et al. 2004***)
Invasive species	Tamarisk (USA), Alaska lupin (Iceland)	Reduction of biodiversity, Stalinization (e.g., ***Lee et al. 2006***)	Change in water balance (e.g., ***Ladenburger et al. 2006***)
Pollution	Tropospheric ozone, toxic waste, oil spills, exhaust, pesticides increased soot emissions (e.g., ***Pagliosa and Barbosa, 2006***)	Reduction in breeding success and biodiversity, species mortality, health impairment, enhanced melting of snow and ice (e.g., ***Lee et al., 2006***)	Direct and indirect aerosol effects on temperature, albedo and precipitation

Innovations on agrobiodiversity management that reduce vulnerability to climate change (e.g. mitigation through management and adaptation through the genetic improvement of resilient and climate-proof crops) are considered all over the world. Such innovations will greatly assist in addressing these challenges and will ensure enough food, feed, fiber and biofuel supply in the next decades. Furthermore, learning from today's agrobiodiversity management that buffers crops and cropping systems against annual extreme weather variations could help to improve their adaptation to future climate. **Nelson *et al*. (2009)** argued recently that crops and livestock that perform reasonably well in a range of production environments are needed rather than those doing extremely well in a narrow set of climates. And, as indicated by **Challinor *et al*. (2007)**, crop cultivars should adapt to both means and extremes of temperature stresses under climate change.

The volume thus encompasses the wide array of information and options involved in the crucial tasks of anticipating and responding to climate change and its effects on agriculture. It reflects the current state of our collective knowledge and aims to spur cooperative research and practices that may encourage the development of sustainable modes of agriculture in harmony with natural ecosystems under changing climate conditions. The challenge is to develop and maintain agroecosystems that simultaneously adapt to and mitigate our changing climate. Presented herewith is a schematic illustration of alternative modes of land and agroecosystem management in relation to climate change:

The actual application of best management practices depends on the particular combination of the agroecosystem and socio-economic conditions that prevails in each region and in each decade. The important principle, however, is universal: The practice of agriculture must be made both productive and sustainable in the long run. The task of agricultural research and development must therefore be to optimize those requirements and practices within the context and in consideration of changing climate conditions. Finally, these requirements must be made consistent with the need to sustain the livelihoods of the people working the land and the nourishment and health of the wider community.

Through their wonderful book, ***Hillel and Rosenzweig*** **(2011)** have surveyed the many ways that global warming and its associated effects interact with agriculture and addresses how agriculture in turn can both adapt to and mitigate a changing climate. Their overall conclusion is that a multi-criteria optimization approach is needed to improve crop productivity for food security while simultaneously protecting the environment. The goal of this approach is to produce higher yields with reduced greenhouse gas emissions per unit of production and to conserve soil, water, and ecosystem integrity. This challenging goal can be implemented through three major synergistic activities: **(1)** improved fundamental understanding of soil functions and crop physiology, **(2)** targeted breeding programs based on that improved fundamental understanding; and **(3)** advanced agronomic management aimed at intensifying and sustaining productive agricultural land while preserving ecosystems in non-agricultural land.

Many directions for research needed to achieve these overall goals are indicated throughout the handbook. Key areas for further research and knowledge gaps include (for more details about the following topics, please have a look at the splendid book of the great scientist Prof. Hillel and his friend Cynthia Rosenzweig:

(1) Broad-scale interactions: theses include:

- *More complete understanding of the carbon and nitrogen cycles*
- *Ensuring food security in a changing climate*

(2) Measuring and modeling CO_2 and temperature effects: these include:

- *High CO_2 experiments*
- *Improving crop models*

(3) Climate, pests, and regions

- *Developing climate change scenarios for agriculture*
- *Characterizing crop water use*
- *Assessing crop-pest interactions*
- *Projecting impacts on agricultural regions*

(4) Adaptation and mitigation

- *Designing adaptation*
- *Fostering mitigation*
- *Integrating economics*

(5) General:

- Establish closer relationships with decision-makers for research so that the results can be targeted to their needs, recognizing that climate change is only one part of the future that will affect agricultural decisions.
- Extend climate change research community to include both academic and “shake holder-focused” practitioners.

Climate change encompasses an exceedingly complex array of dynamic processes, with specific combinations or interactions in each agricultural region. Climate change, increases in carbon dioxide, and changes in the global nitrogen cycle are but a few of the potentially fateful factors involved. The task now is to study these and the other myriad of factors interactively, so as to prepare appropriate and effective mitigation and adaptation strategies. While environmental policy for agriculture has traditionally been tied to water quality and soil conservation, these policies are being expanded to include limits on emissions of greenhouse gases and even potential reductions. Accomplishing this while producing nutritious food under changing climate conditions for the coming population on Earth of 9 billion people is the great challenge facing agricultural researchers, planners, and practitioners today (***Hillel and Rosenzweig, 2011***).

The 1980s and 1990s and the early years of the twenty-first century have brought unusually warm years for the globe as a whole, which shows the global average temperature since 1850, the period for which the instrumental record is available with good accuracy and coverage. An increase over this period has taken place of 0.76 ± 0.19 °C. The two warmest years in the record are 1998 and 2005, 1998 ranking highest on one estimate and 2005 highest on two other estimates. Also 12 of the 13 years 1995 to 2007 rank amongst the 13 warmest years in the whole record. A further striking statistic is that each of the first eight months of 1998 was *very likely*1 the warmest of those months in the record up to that date. Although there is a distinct trend in the record, the increase is by no means a uniform one. In fact, some periods of cooling as well as warming have occurred and an obvious feature of the record is the degree of variability from year to year and from decade to decade (***Houghton, 2009***).

Note also that there has been little if any average increases in warming during the years 2001–2006. Some have tried to argue that this shows the warming is over. However, seven years of record is too short a period to establish a trend. Although the year 2007 was slightly cooler that 2006, the first seven years of the twenty-first century were on average nearly 0.2 °C warmer than the last seven years of the twentieth century, even though 1998 was the warmest year so far. Further, studies of interannual variability in the record demonstrate the strong influence of variations in El Niño and suggest that interannual variability may continue to offset anthropogenic warming until around 2009.

Since we live in the atmosphere the variables commonly used to describe climate are mainly concerned with the atmosphere. But climate cannot be described in terms of atmosphere alone. Atmospheric processes are strongly coupled to the oceans; they are also coupled to the land surface. There is also strong coupling to those parts of the Earth covered with ice (the cryosphere) and to the vegetation and other living systems on the land and in the ocean (the biosphere). These five components – atmosphere, ocean, land, ice and biosphere – together make up the climate system (***Houghton, 2009***).

Climate changes in different regions of the world showed that it is likely to vary a great deal from place to place. For instance, in some regions precipitation will increase, in other regions it will decrease (**Table 1.2**). Not only is there a large amount of variability in the character of the likely change, there is also variability in the sensitivity of different systems to climate change. Different ecosystems, for instance, will respond very differently to changes in temperature or precipitation. There will be a few impacts of the likely climate change that will be positive so far as humans are concerned. For instance, in parts of Siberia, Scandinavia or northern Canada increased temperature will tend to lengthen the growing season with the possibility in these regions of growing a greater variety of crops. Also, in winter there will be lower mortality and heating requirements. Further, in some places, increased carbon dioxide will aid the growth of some types of plants leading to increased crop yields. However, because, over centuries, human communities have adapted their lives and activities to the present climate, most changes in climate will tend to produce an adverse impact. If the changes occur rapidly, quick and possibly costly adaptation to a new climate will be required by the affected community. An alternative might be for the affected community to migrate to a region where less adaptation would be needed – a solution that has become increasingly difficult or, in some cases, impossible in the modern crowded world. It is relatively easy to consider the effects of a particular change (in say, sea level or water resources) supposing nothing else changes. But other factors will change. Some adaptation, for both ecosystems and human communities, may be relatively easy to achieve; in other cases, adaptation may be difficult, very costly or even impossible. In assessing the effects of global warming and how serious they are, allowance must be made for response and adaptation. The likely costs of adaptation also need to be put alongside the costs of the losses or impacts connected with global warming (***Houghton, 2009***).

Table 1.2: Twentieth-century changes in the Earth's atmosphere, climate and biophysical system (adapted from ***Houghton, 2009***)

Indicator	*Observed changes*
Concentration indicators	
Atmospheric concentration of CO_2	280 ppm for the period 1000–1750 to 368 ppm in year 2000 (31 ± 4% increase) – 380 ppm in 2006
Terrestrial biospheric CO_2 exchange	Cumulative source of about 30 GtC between the years 1800 and 2000; but during the 1990s a net sink of about 10 ± 6 GtC
Atmospheric concentration of CH_4	700 ppb for the period 1000–1750 to 1750 ppb in year 2000 (151 ± 25% increase) – 1775 ppb in 2005
Atmospheric concentration of N_2O	270 ppb for the period 1000–1750 to 316 ppb in the year 2000 (17 ± 5% increase) – 319 ppb in 2005
Tropospheric concentration of O_3	Increased by 35 ± 15% from the years 1750 to 2000, varies with region
Stratospheric concentration of O_3	Decreased since 1970, varies with altitude and latitude
Atmospheric concentrations of HFCs, PFCs and SF_6	Increased globally over the last 50 years
Weather indicators	
Global mean surface temperature	Increased by 0.6 ± 0.2 °C over the twentieth century – 0.74 ± 0.18 over 100 years 1906–2005; land areas warmed more than the oceans (*very likely*)
Northern hemisphere surface temperature	Increase over the twentieth century greater than during any other century in the last 1000 years; 1990s warmest decade of the millennium (*likely*)
Diurnal surface temperature range	Decreased over the years 1950 to 2000 over land; night-time minimum temperatures increased at twice the rate of daytime maximum temperatures (*likely*)
Hot days/heat index	Increased (*likely*)
Cold/frost days	Decreased for nearly all land areas during the twentieth century (*very likely*)
Continental precipitation	Increased by 5–10% over the twentieth century in the northern hemisphere (*very likely*), although decreased in some regions (e.g. north and west Africa and parts of the Mediterranean)
Heavy precipitation events	Increased at mid and high northern latitudes (*likely*)
Drought	Increased summer drying and associated incidence of drought in a few areas (*likely*). Since 1970s, increase in total area affected in many regions of the world (*likely*)
Tropical cyclones	Since 1970s, trend towards longer lifetimes and greater storm
Intense extratropical storms	intensity but no trend in frequency (*likely*) Since 1950s, net increase in frequency/intensity and poleward shift in track (*likely*)
Biological and physical indicators	
Global mean sea level	Increased at an average annual rate of 1–2 mm during the twentieth century – rising to about 3 mm from 1993–2003
Duration of ice cover of rivers and lakes	Decreased by about two weeks over the twentieth century in mid and high latitudes of the northern hemisphere (*very likely*)
Arctic sea-ice extent and thickness	Thinned by 40% in recent decades in late summer to early autumn (*likely*) and decreased in extent by 10–15% since the 1950s in spring and summer
Non-polar glaciers	Widespread retreat during the twentieth century
Snow cover	Decreased in area by 10% since global observations became available from satellites in the 1960s (*very likely*)

Permafrost	Thawed, warmed and degraded in parts of the polar, sub-polar and mountainous regions
El Niño events	Became more frequent, persistent and intense during the last 30 years compared to the previous 100 years
Growing season	Lengthened by about one to four days per decade during the last 50 years in the northern hemisphere, especially at higher latitudes
Plant and animal ranges	Shifted pole ward and up in elevation for plants, insects, birds and fish
Breeding, flowering and migration	Earlier plant flowering, earlier bird arrival, earlier dates of breeding season and earlier emergence of insects in the northern hemisphere
Coral reef bleaching	Increased frequency, especially during El Niño events
Economic indicators	
Weather-related economic losses	Global inflation-adjusted losses rose by an order of magnitude over the last 50 years. Part of the observed upward trend is linked to socio-economic factors and part is linked to climatic factors

Note: This table provides examples of key observed changes and is not an exhaustive list. It includes both changes attributable to anthropogenic climate change and those that may be caused by natural variations or anthropogenic climate change. Confidence levels are reported where they are explicitly assessed by the relevant Working Group of the IPCC.

1.2.2 *Agrometeorology*

In his remarkable encyclopedia "*Encyclopedia of weather and climate*", **Allaby (2007)** defined the meteorology science and all related sciences in the following definitions:

Item	***Definition***
Meteorology	The scientific study of the atmospheric phenomena that produce weather, and especially the application of this study to the forecasting of weather. The word is derived from the Greek word *meteorologia,* which in turn is derived from *meteoron,* which means "of the atmosphere" and *meteoros,* which means "lofty."
Agrometeorology	Agrometeorology is the study of weather systems in terms of their effects on farming and horticulture and the provision of meteorological services for farmers and growers. Agricultural and horticultural weather forecasts provide information on the likely effect of forthcoming weather on particular crops.
Macrometeorology	Macrometeorology is the scientific study of the atmosphere at the largest scale, including the general circulation and the development and behavior of air masses and large weather systems.
Mesometeorology	Mesometeorology is the study of weather systems that extend horizontally for about 0.6–60 miles (1–100 km). Satellite images make it possible for meteorology to be conducted at this scale. These show the clouds associated with such phenomena as frontal systems, squall lines, and tropical cyclones as well as showing large individual cumulonimbus clouds associated with thunderstorms and the gust fronts they produce. Through its widespread use of satellite images, modern weather forecasting relies heavily on mesometeorology.
Micrometeorology	Micrometeorology is the scientific study of the atmospheric conditions that prevail inside a microclimate. It includes the study of phenomena that are very important locally, such as the behavior of air as it crosses a particular area of high ground, convective movements and cloud formation that result from uneven heating of the ground, and the turbulent flow that is produced by particular surfaces.
Hydrometeorology	Hydrometeorology specializes in the study of precipitation. Types of precipitation are sometimes called "hydrometeors." This is the aspect of meteorology that is of most

	direct concern to farmers and growers, irrigation engineers, flood-control engineers, designers and managers of hydroelectric schemes, and others with a particular interest in surface waters.
Biometeorology	Biometeorology is the scientific study of the relationship between living organisms and the air around them. This includes the effect that organisms have on the air, through photosynthesis, respiration, and transpiration, as well as the emission of gases and particulate material by plants and animals, and as a consequence of human activity. Plants also affect the atmosphere by shading the ground beneath them and by intercepting precipitation. This produces distinct microclimates in shaded and unshaded areas. The study also includes the response of plants and animals to atmospheric conditions. Plants wilt during a drought, for example, and many animals seek shade when the sky is clear and the sunshine intense. Biometeorology also includes specialized subdisciplines, such as agrometeorology.

Agrometeorology, abbreviated from agricultural meteorology, puts the science of meteorology to the service of agriculture, in its various forms and facets, to help with the sensible use of land, to accelerate the production of food, and to avoid the irreversible abuse of land resources (***Smith, 1970***). Agrometeorology is also defined as the science investigating the meteorological, climatological, and hydrological conditions that are significant to agriculture owing to their interaction with the objects and processes of agriculture production (***Molga, 1962***).

The definition of biometeorology adopted by the International Society of Biometeorology (ISB) states, "Biometeorology is an interdisciplinary science dealing with the application of fields of meteorology and climatology to biological systems" (***Hoppe, 2000***). The general scope includes all kinds of interactions between atmospheric processes and living organisms — plants, animals, and humans. By this definition, it becomes evident that there are roughly three subbranches of biometeorology: plant, animal, and human biometeorology (***Hoppe, 2000***). The domain of agrometeorology is the plant and animal subbranches. The third subbranch, human biometeorology, is outside the scope of agrometeorology (***Mavi and Tupper, 2004***).

Agrometeorology is an interdisciplinary science in which the main scientific disciplines involved are atmospheric sciences and soil sciences, which are concerned with the physical environment, and plant sciences and animal sciences (including their pathology, entomology, and parasitology, etc.), which deal with the contents of the biosphere. The interdisciplinary nature of agrometeorology is both its greatest strength and its greatest weakness (***Hollinger, 1994***). The strength is obtained from an agricultural meteorologist's understanding of the interactions of physical and biological worlds (***Mavi and Tupper, 2004***).

The agriculture industry is the most sensitive to variability in weather and climate. Throughout the world, efforts have been made to provide agriculture with a specifically focused weather service. Most countries of the world have developed programs to provide agroclimatological services. Unfortunately, in many countries there is a lack of coordination and cooperation to link agencies representing agriculture and meteorology in their efforts to advise farmers of weather-related risk management. This lack of cooperation has adversely affected improvements and further development in agro-advisory services. Furthermore, due to a lack of financial support, the network of meteorological stations does not adequately cover various agrometeorological zones to meet potential needs. Conflicts within and between countries often halt the collection and exchange of weather data. This has a detrimental impact on projects in which analysis of weather and climate data is attempted (***Mavi and Tupper, 2004***).

Over the past 100 years, human activities have significantly altered the earth's atmosphere. Increases in the concentrations of greenhouse gases have led to warming of the earth's surface. An accumulating body of evidence suggested that by the last decade of the twentieth century global warming had already made significant negative impacts in a large number of regions. The menace of global climate change became a central issue of investigation in the 1990s and beyond. The investigations considered the effects of global warming on individual plants, plant stands, and entire vegetation units from regional to global scales (***Overdieck, 1997***). The investigations were not confined only to plants; the impact on hydro-resources, livestock, insect pests, and diseases has also been investigated (***Mavi and Tupper, 2004***).

Weather plays the dominant role in farm production. Weather is always variable, and farmers have no control over this natural phenomenon. Climate variability persisting for more than a season and becoming a drought puts great pressure on land and vegetation. Normal land-use and management systems become incompatible with prevailing climate, and farm production is drastically reduced. Abnormalities such as drought and associated farm losses are not very frequent, but losses due to short-term climate variability and sudden weather hazards such as flash floods, untimely rains, hailstorms, and severe frost do occur year after year. Losses in transport, storage, and due to parasites, insects, and diseases are the indirect results of abnormalities in weather conditions and are a recurring feature. It has been estimated (***Mavi, 1994***) that, directly and indirectly, weather contributes to approximately three-quarters of annual losses in farm production (***Mavi and Tupper, 2004***).

Three types of weather forecasts are prepared by the weather forecasting agencies in most of the countries of the world. These are the short-range forecast valid for 48 hours, the medium-range or extended forecast valid for five days, and the long-range or seasonal forecast valid from a month to a season. Each of these forecasts has a role to play in agriculture. Whereas short-range forecasts are most valuable in daily farm operations, medium range and seasonal forecasts are important in longer-term farm operations and planning. Based on these forecasts, farmers can make the best use of favorable weather conditions and adjustments can be made for adverse weather (**Figure 1.4;** ***Mavi and Tupper, 2004***).

1.2.3 *Agroecosystem*

An agroecosystem is a complex community of organisms inhabiting a particular managed domain and operating on at least three trophic levels: crop, pest, and pest–predator. These trophic levels interact to determine the severity of infestations by insect pests. Humans are an essential part of agroecosystems as they work to manipulate crop productivity. Humans also intervene inadvertently by introducing exotic insect species to new environments and by extending the geographic range of host crops. Agroecosystems have evolved over long periods of time by adapting in different ways and to different degrees to the levels of climate variability experienced. However, the degree to which an agricultural system is adapted to climatic variation and how levels of adaptation change over time are difficult to measure (**Figure 1.5; *Rosenzweig and Hillel, 2008***).

Agroecosystems are made up of many species besides crops. Some, such as pollinating bees and soil mycorrhizae, are beneficial to crops, whereas others, such as weeds and nematodes, become pests when they compete with or prey upon crop plants to an extent that reduces crop productivity. All such organisms, as well as all crops, are affected by climate variability in their own specific ways. Climate affects not just agricultural crops but also their associated pests. Pests are organisms and microorganisms that harm crops and reduce their value before or after harvest. The major pests of crops are weeds, insects, and pathogens. The distribution and proliferation of weeds, fungi, and insects are determined to a large extent by climate. Variability in crop yields is often associated with incidence of pests and diseases, which is in turn linked to meteorological conditions. Some analyses indicate that there have been increases in the proportion of crops lost to pests in recent decades (***Rosenzweig et al. 2001***).

Agroecosystems play a significant role in climate change, both by manifesting climate change impacts and as major contributors of greenhouse gases. Presented herewith is a schematic illustration of alternative modes of land and agroecosystem management in relation to climate change (**Figure 1.6**):

(1) An *exploitive mode*, in which the natural vegetation is eradicated, leading to denudation of the land, loss of biodiversity, decomposition and depletion of organic matter with consequent emissions of greenhouse gases (CO_2, CH_4, N_2O), leaching of nutrients, erosion by wind and water, deterioration of soil structure, wasteful use of energy and water, and gradual (often irreversible) loss of productivity.

(2) A *sustainable mode*, in which the production of crops and livestock is able to adapt to changing climate conditions because it is designed to minimize soil and ecosystem degradation by means of minimal tillage and precision application of nutrients, integrated pest management (including biological control methods), conservation of energy, improvement of soil stability and fertility by organic matter enrichment and carbon sequestration, efficient use of water, and the overall integration of production within a stable and healthy ecosystem (***Hillel and Rosenzweig, 2011***).

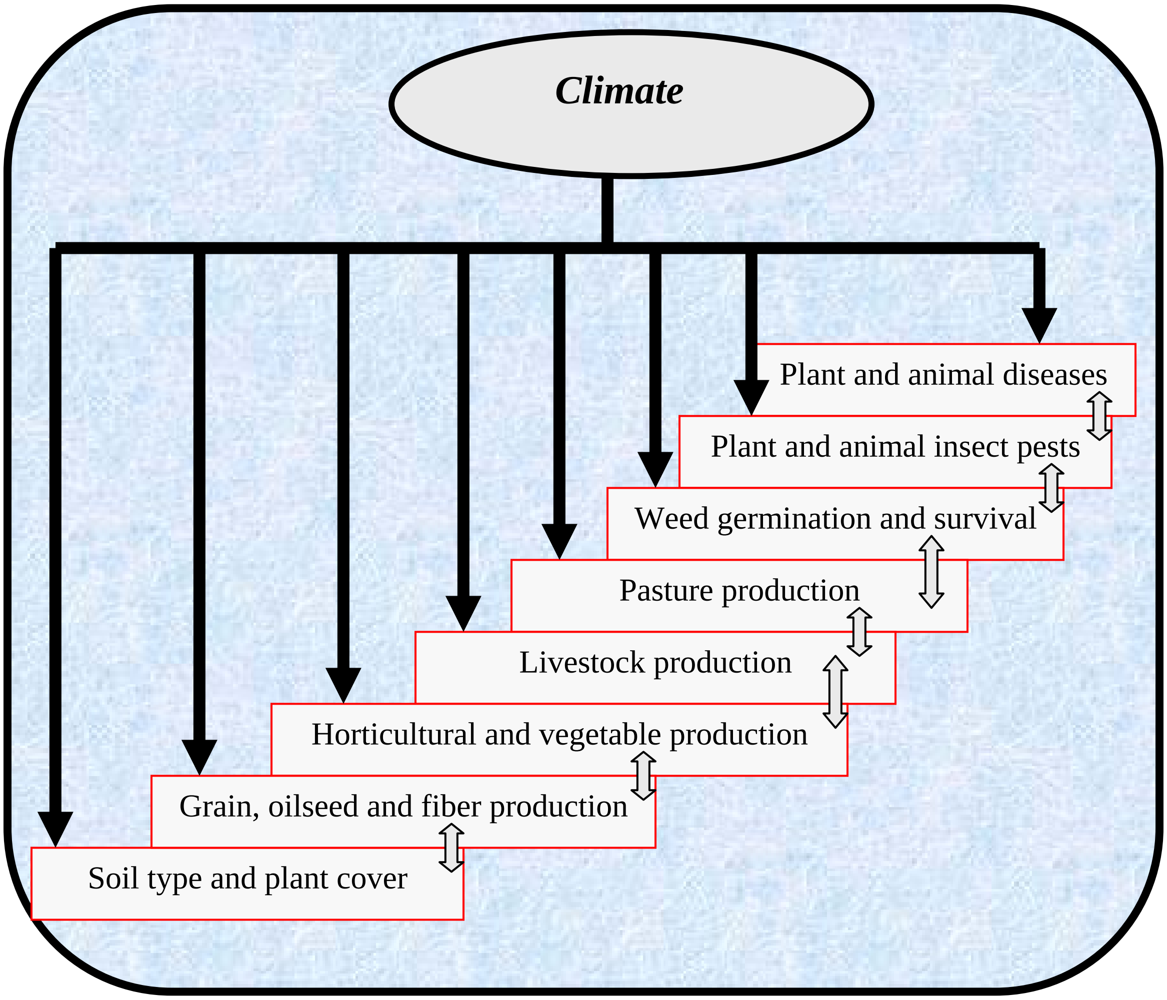


Figure 1.4: Climate and agricultural production (modified from ***Mavi and Tupper, 2004***)

The actual application of best management practices depends on the particular combination of the agroecosystem and socio-economic conditions that prevails in each region and in each decade. The important principle, however, is universal: The practice of agriculture must be made both productive and sustainable in the long run. The task of agricultural research and development must therefore be to optimize those requirements and practices within the context and in consideration of changing climate conditions. Finally, these requirements must be made consistent with the need to sustain the livelihoods of the people working the land and the nourishment and health of the wider community (***Hillel and Rosenzweig, 2011***).

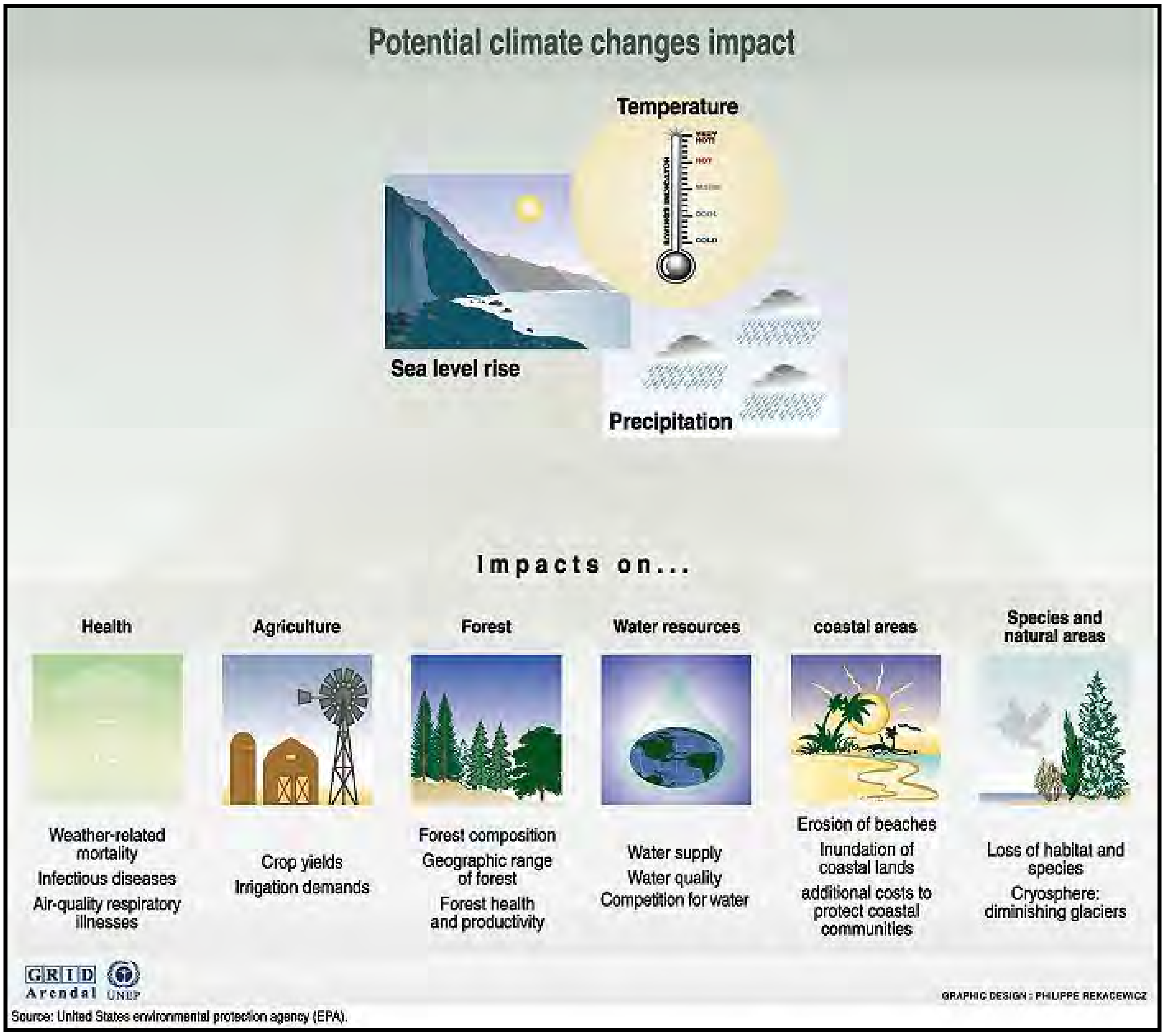


Figure 1.5: Potential climate changes impact according to IPCC 92 scenarios (http://www.grida.no/publications/vg/climate/page/3073.aspx/ 25.12.2011)

1.2.4 *Agrobiodiversity*

Wood and Lenné (1999) provided a broad, technically sound, functional view of agrobiodiversity: what it is made up of; how it is managed; how it is conserved; and how it can best be utilized. This book covered the status of the concept and usage of the word agrobiodiversity and its relation to wild biodiversity; the components of agrobiodiversity and how they relate together functionally, how they impact on agricultural production, and how agrobiodiversity can best be managed for sustained food production; and whether this extensive knowledge of the management of agrobiodiversity can provide models and practices for the wider management of bio diversity. Emphasis was given to tropical agrobiodiversity as there is more of it and its management is more important for the food security for the poor.

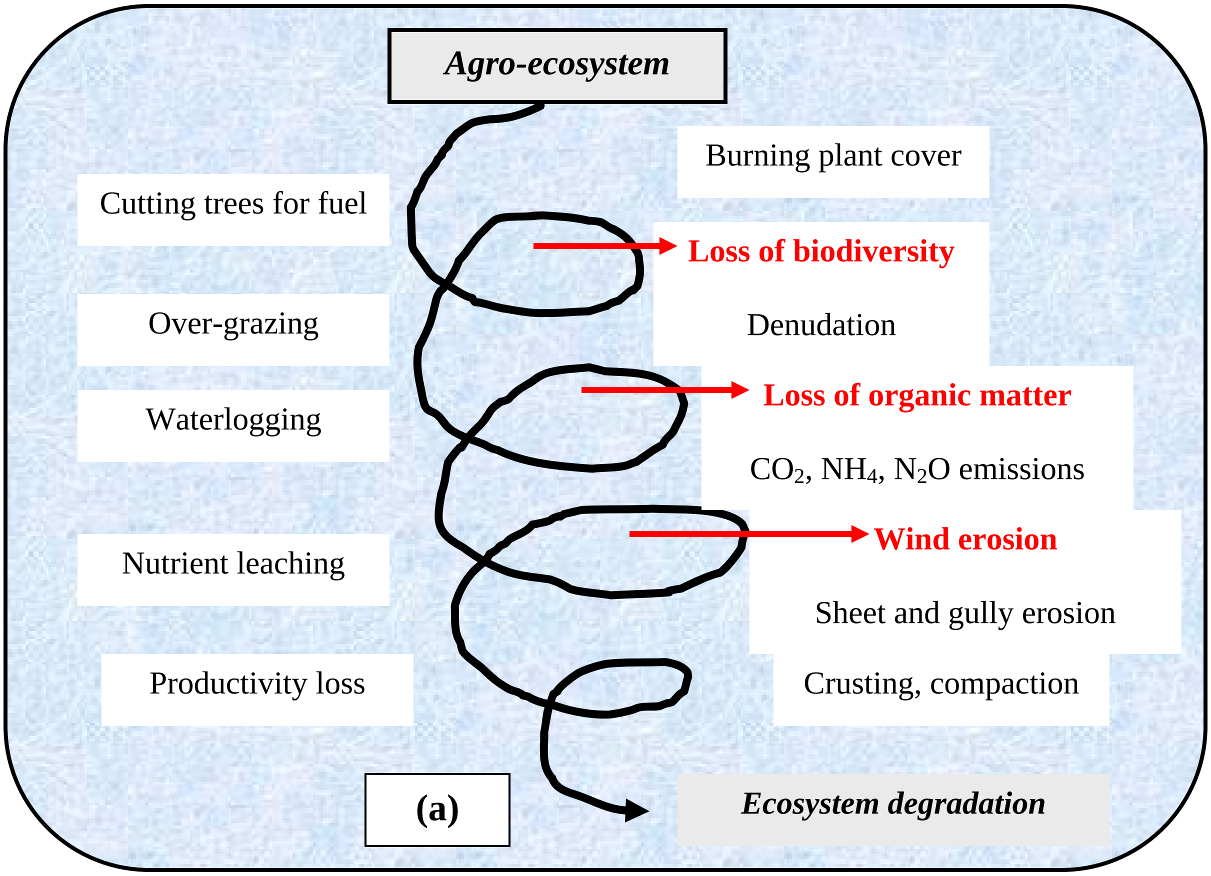
Biodiversity in agroecosystems can be as varied as the crops, weeds, arthropods, or microorganisms involved or the geographical location and climatic, edaphic, human, and socioeconomic factors. In general, the degree of biodiversity in agroecosystems depends on four main characteristics of the agroecosystem (***Southwood and Way, 1970***):

- • The diversity of vegetation within and around the agroecosystem
- • The permanence of the various crops within the agroecosystem
- • The intensity of management
- • The extent of the isolation of the agroecosystem from natural vegetation

The biodiversity components of agroecosystems can be classified in relation to the roles they play in the functioning of cropping systems. According to this, agricultural biodiversity can be grouped as follows (***Swift and Anderson, 1993***):

- *Productive biota:* crops, trees, and animals chosen by farmers that play a determining role in the diversity and complexity of the agroecosystem
- • *Resource biota:* organisms that contribute to productivity through pollination, biological control, decomposition, etc.
- *Destructive biota:* weeds, insect pests, microbial pathogens, etc., that farmers aim at reducing through cultural management (**Figure 1.7;** ***Altieri and Nicholls, 2004***).

Biodiversity refers to all living things and the interactions between them: a vast array of organisms with an almost infinite complexity of relationships. Agricultural biodiversity, that is, ‘agrobiodiversity’, is an exceptionally important subset of biodiversity. Agrobiodiversity has been defined by **Qualset *et al*. (1995)** as including all crops and livestock and their wild relatives, and all interacting species of pollinators, symbionts, pests, parasites, predators and competitors. Agrobiodiversity through agriculture, that is, the management of the interactions between crops and domestic animals and their associated biodiversity and the environment, provides most of our food with less than 5% coming from the wild. Most of our food is also derived directly or indirectly from plants. It has been estimated that more than 80% of our calories and edible dry weight comes from crop plants (***Evans, 2003***). Less than 20 species provide most of the world’s food and three staple crops – rice, wheat and maize – account for about 60% of the calories and 56% of the protein that humans consume directly from plants. Wheat and rice alone contribute about 44% of edible dry weight directly; root crops less than 10%; sugar crops about 8%; vegetables and fruit about 7%; and pulses about 3%. Future global food security is therefore firmly anchored in improved productivity and appropriate management and use of crop plant agrobiodiversity, especially of rice, wheat and maize.


Agro-ecosystem
Burning plant cover
Cutting trees for fuel
Loss of biodiversity
Over-grazing
Denudation
Waterlogging
Loss of organic matter
CO2, NH4, N2O emissions
Nutrient leaching
Wind erosion
Sheet and gully erosion
Productivity loss
Crusting, compaction
(a)
Ecosystem degradation

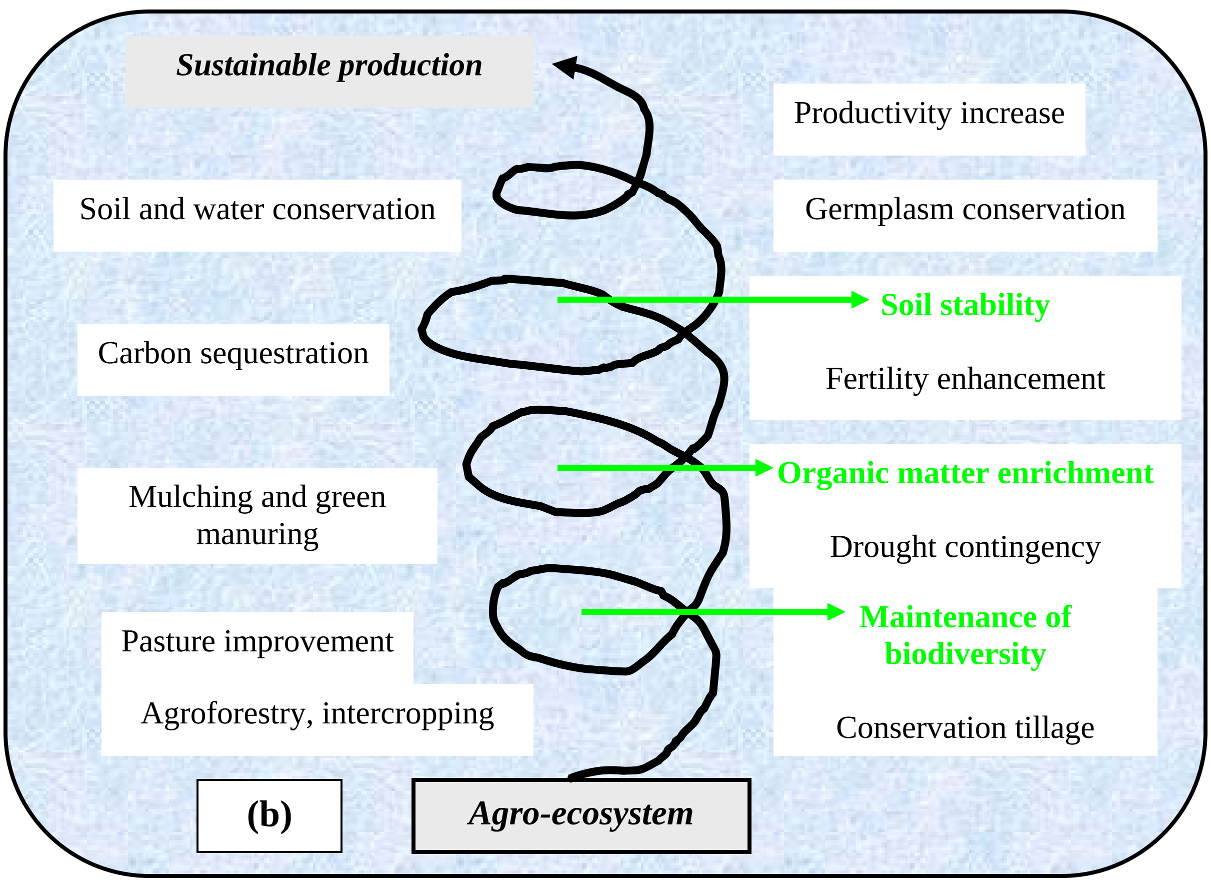

Sustainable production
Productivity increase
Soil and water conservation
Germplasm conservation
Soil stability
Carbon sequestration
Fertility enhancement
Organic matter enrichment
Mulching and green manuring
Drought contingency
Maintenance of biodiversity
Pasture improvement
Agroforestry, intercropping
Conservation tillage
(b)
Agro-ecosystem

Figure 1.6: Schematic illustration of alternative modes of land and agroecosystem management in relation to climate change: (a) exploitive mode; (b) sustainable mode (adapted from ***Hillel and Rosenzweig, 2011***).

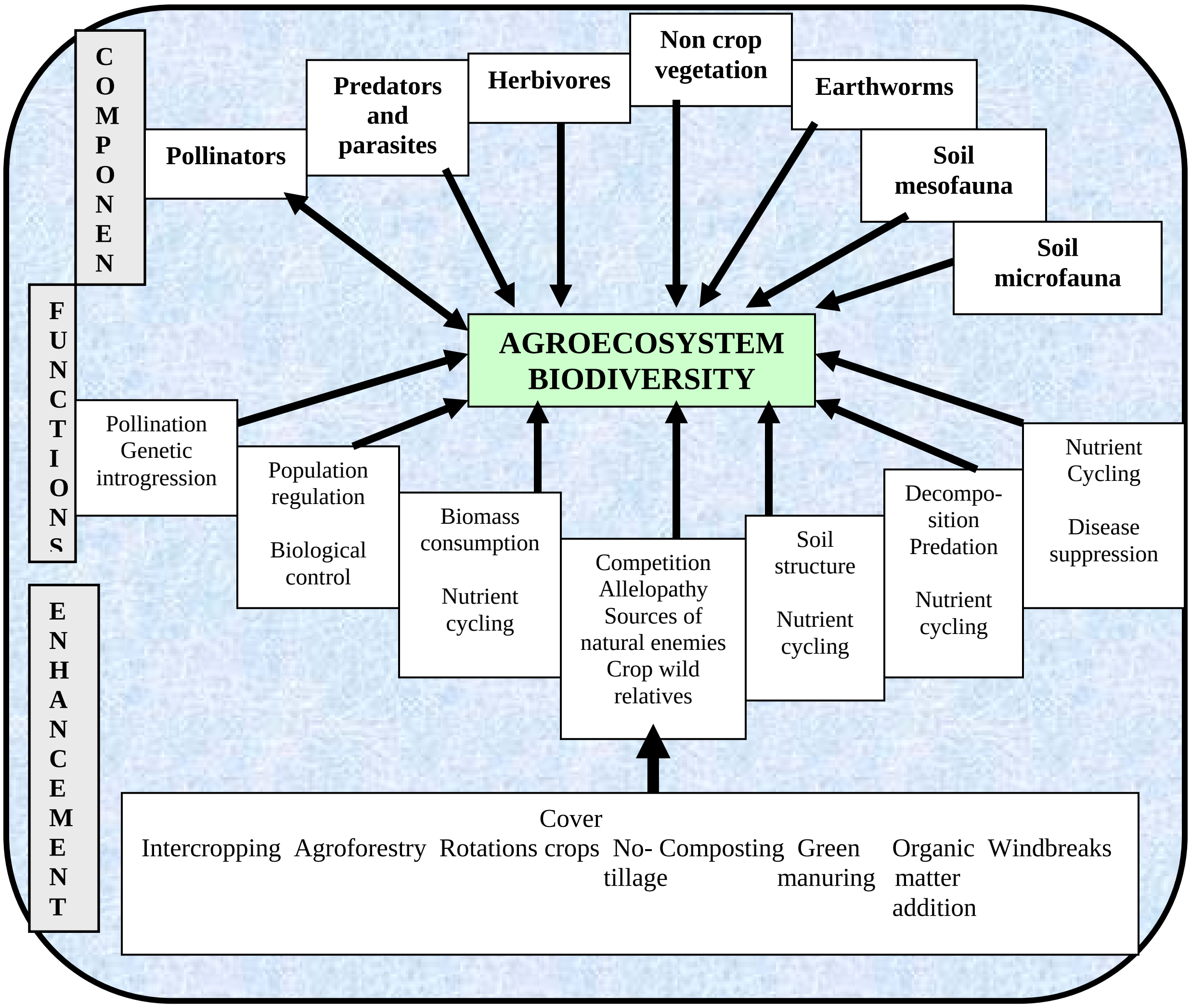


Figure 1.7: The components, functions, and enhancement strategies of biodiversity in agroecosystems (adapted from ***Altieri, and Nicholls, 2004***).

But agrobiodiversity includes far more than the husbandry of crops and farm animals. As **Brookfield (1998)** observed, 'the dynamism of agrodiversity, a constantly changing patch work of relations between people, plants, and their environment, always coping with new problems, always finding new ways', the dynamic interactions of this food agro biodiversity with other agrobiodiversity in agroecosystems – both beneficial and harmful and both above- and below-ground – are critical to determining if we harvest more or less food. The almost limitless combinations of more or less intensive management, the varied local biotic and abiotic environments, and the human ability to introduce crops and their pests and diseases from elsewhere, and then select within and between these varieties, resulted in a diversity of planned agrobiodiversity.

The most significant recent development for agrobiodiversity internationally has been the coming into force of the International Treaty for Plant Genetic Resources (ITPGR) in 2004 (www.planttreaty.org). The International Treaty (IT) further reinforced the perceived synonymy between ‘crop diversity’ and agrobiodiversity, again ignoring the importance of crop-associated diversity. This was closely followed by the establishment of the Global Crop Diversity Trust in 2006, an independent international organization, which endeavors to support the conservation of distinct and important crop diversity (www.croptrust.org). In the past 2 years, the Trust has raised $100 million in contrast to the IT for which no significant new funding has emerged (***Lenné and D. Wood, 2011***).

There also appears to be a growing consensus among agricultural and environmental scientists that they must work together climate change are linked in important ways (***Nelson, 2009***). Rising temperatures, altered rainfall patterns and more frequent extreme events will increasingly affect crop production and agriculture, but precisely where and how much is still uncertain. Agriculture can help Mitigate climate change and poor farmers in developing countries will need help in adapting to climate change. In fact, the advances in modern agriculture achieved in the past 40 years have helped slow the pace of global warming by reducing the amount of biomass burned when land is cleared for farming (***Bergeron, 2010***). It has been estimated that emissions have been reduced by over 0.5 trillion t of carbon dioxide. For example, irrigated rice under multiple cropping sequesters considerable amounts of carbon (***IRRI, 2010***). Adaptation of staple food crops through plant breeding and mitigation through improved management will support climate change goals of enhancing the wellbeing of people who manage and depend on agriculture, especially in the developing world. The failure of the 15th Conference of Parties of the UN Framework Convention on Climate Change (UNFCCC) held in Copenhagen in December 2009 to reach a consensus and agree a global plan of action that includes agrobiodiversity management is therefore very disappointing.

Agricultural scientists quite rightly continue to concentrate on science and the increasing need to develop improved technologies to meet the food needs of an ever-expanding global population. Hence opportunities continue to be lost to promote the importance of agrobiodiversity to food security internationally. Although they have limited time to contribute to international debates, scientists should try to seize appropriate opportunities to participate in policy debates to influence investment decisions on the science that underpins food production:

Agriculture is the largest global user of biodiversity (***Wood and Lenné, 1999***). Agriculture has selected and added value to wild biodiversity over more than 10,000 years of managing agrobiodiversity. Agriculture has conserved biodiversity on the hoof and as seed and planting materials over this long period. Agriculture extracts value from biodiversity at each harvest or cull, but nurtures the productive and renewable base. Indeed, it is certain that the most immediately valuable part of global biodiversity is the agrobiodiversity on which farming and, in turn, global food security, depends (**Table 1.4**).

Wood and Lenné (1999) was premised on the fact that agrobiodiversity is irreplaceably important in its own right, for providing most of our food. The management of agrobiodiversity will determine our future, both in cities and the countryside. Agroecosystems – mediated through agrobiodiversity – have always provided the essential ecosystem service of food production, and can be designed to deliver a further range of ecosystem services as needs and knowledge change. Present knowledge extends from a greater appreciation of traditional agriculture and the needs of farmers, through classical agricultural research in animal husbandry, genetics, statistics, replicated experiments, plant breeding, agronomy, crop protection, rural sociology, information management and many more, through to biotechnology (***Lenné and D. Wood, 2011***).

1.2.5 *Impacts of climate change on agrobiodiversity*

Global yield losses due to global warming have amounted to 40 million t or US$5 billion yearly for wheat, maize and barley since 1981 (***Lobell and Field, 2007***). Furthermore, crop modelling shows that climate change will continue to reduce agricultural production, thus reducing food availability and thereby affecting food security and farm incomes (***Battisti and Naylor, 2009***). The Intergovernmental Panel on Climate Change in its 4^{th} Assessment Report confirms that indeed changing climate will bring a high intensity and frequency of storms, drought and flooding, weather extremes, altered hydrological cycles and precipitation, which, without doubt, will affect agricultural production. These impacts will depend on region, growing season, weather patterns and crops. For example, severe crop losses are expected for cotton, maize and soybean in the USA by the end of this century due to warmer temperatures (***Schlenker and Roberts, 2009***). Grain harvests in China and South Asia may also drop by 37% and 30%, respectively, by 2050 due to weather extremes, whereas extreme drought (i.e. doubling severity and frequency) in north-east China could result in 12% crop losses (or 13.8 million t) by 2030 (***Bloomberg News, 2009***). Although models provide an important tool for understanding and assessing future climate impacts, results from modelling should be taken with caution because their spatial scales could fail to capture topographical or microclimatic buffering, and they do not oft en consider the wide acclimation capacity of animals and plants. Hence, as stated by **Tubiello *et al*. (2007)**, understanding the key dynamics characterizing interactions between elevated CO_2 and changes in climate variables (e.g. extremes, soil and water quality, pests, pathogens) and ecosystem vulnerability remains as priority research for quantifying better the impacts of climate change on crops and pastures (***Lenné and Wood, 2011***).

Table 1.4: Agrobiodiversity management interventions for food security (adapted from ***Lenné and Wood, 2011***)

Strategies	*Interventions*
Increasing investment in agricultural research and development	
Improved genetic resource management and utilization	Safe and secure management and conservation of plant genetic resources Informed and targeted crop and varietal introduction e.g. fruits and vegetables Exploring crop genomes including wild relatives for useful traits
Increased staple food crop production	Revitalizing yield growth in rice and wheat in high potential systems Expanded use of crop hybrids and higher-yielding varieties Fostering local and national quality seed systems Expanded use of genomics, MAS, genetic modifications, high-throughput systems Increasing photosynthetic efficiency: C3 plants e.g. rice to C4
Reduced losses caused by biotic stresses	Improved deployment of existing and novel pest and disease resistances Innovative management of crop-associated biodiversity for diseases Integrated pest management through crop-associated biodiversity Enhanced use of biological control Integrated weed management through crop-associated biodiversity
Reduced losses caused by abiotic stresses	Enhanced deployment of resistances to heat, cold, drought, submergence, salinity, and infertile and toxic (e.g. Al, Fe) soils
Improved soil fertility and conserving soil	Wider use of green manure crops Innovative management of soil-based crop-associated biodiversity Zero-tillage, crop rotation, intercropping, mulching, biochar etc.
Increased efficiency of water and fertilizer use	Enhanced deployment of more efficient crop varieties e.g. aerobic rice Improving existing nitrogen fixation processes Developing nitrogen fixation systems in other crops Enhancing crop phosphorus-uptake through improved mycorrhizal processes
Improve the nutritional quality of food	Enhanced deployment and promotion of more nutritional foods Development and deployment of crop varieties with higher protein, mineral and vitamin contents Establishing processing facilities and promoting processing to preserve nutritional quality
Improved food safety	Elimination of potentially toxic compounds from foods Reducing microbial toxins in foods that impact on human health
Relevant knowledge and technologies delivered to small farmers	Most of the above where appropriate, practical and affordable
Expanding social and safety net interventions	
Appropriate and practical food crop diversity promoted	Home gardens, especially for vegetables and fruits Community-based food production options in urban areas
Strengthening markets and facilitating trade	
Food crop market chains improved	Reducing post-harvest losses and inefficiencies in the market chain Extending storage-life or delaying ripening Connecting small farmers equitably into market chains Improving infrastructure and transport linkages
International and regional trade fostered and increased	Building capacity of small farmers to meet quality and regulatory standards Connecting small farmers to high value and export value chains Facilitating equitable and rule-based international and regional trade
Improving policy support for food security	Developing and expanding policies based on proven scientific approaches Involvement of scientists in informing policy makers Avoiding policies based on unproven and fl awed approaches

Changes in climate could also rapidly shift plant distributions because some species will expand in newly favorable areas and others will decline in increasingly adverse locations (***Kelly and Goulden, 2008***). For example, models suggest that at least 50% of the plant species in Europe could be vulnerable or threatened by 2080 (***Thuiller et al. 2005***). In this regard, **Lane and Jarvis (2007)** using the Ecocrop model (http:// ecocrop.fao.org) projected the impact of climate change by 2055 on suitable areas for most important staples and cash crops, including those of the multilateral system of the International Treaty on Plant Genetic Resources for Food and Agriculture. The largest gain in suitable areas is likely to be in Europe (3.7%) whereas sub-Saharan Africa and the Caribbean may suffer 2.6% and 2.2% declines of land area, respectively. Although their modelling suggests some crop gains in suitable areas (e.g. 31% for pearl millet, 18% for sunflower, 15% for chickpea and 14% for soybean), these 'new crop lands' are in regions where they are not important local food staples, e.g. 10% increase for pearl millet in Europe and the Caribbean rather than in sub- Saharan Africa and India (***Lenné and Wood, 2011***).

Agrobiodiversity remains the main raw material for agroecosystems to cope with climate change because it can provide traits for plant breeders and farmers to select resilient, climate-ready crop germplasm and release new cultivars. However, modelling research suggests that some crop wild relatives may become extinct by 2055 (***Jarvis et al. 2008***), e.g. 8% of *Vigna*, 12% of tuber-bearing *Solanum* and 61% of *Arachis* species. Collecting samples of endangered species to be preserved in gene banks will be the first step, but also protecting the habitats where they thrive should be a must to ensure the *in situ* evolutionary processes of wild species contributing to agrobiodiversity. Furthermore, as noted by recent research of maize, pearl millet and sorghum genetic resources in sub-Saharan Africa (***Burke et al. 2009***), available genetic resources for these crops in gene banks may not be the most useful for adapting them to climate change in this continent. Hence, analogue crop areas for many future climates should be promising locations to focus future collecting and conserving of crop genetic resources (***Lenné and Wood, 2011***).

1.2.6 *IPCC and agrobiodiversity management*

Although the world can cope with climate change by maintaining and using agrobiodiversity, Inter-governmental Panel on Climate Change (IPCC) has not given enough attention to the value of biodiversity for food and agriculture, which will increase with global warming, drought and other stresses. The chapter on agriculture of the 4^{th} IPPC Assessment (***Metz et al. 2007***) does not mention agrobiodiversity (or refer properly to agricultural biodiversity) and how it can contribute to climate change adaptation. There are, in this and other chapters, a few references to biodiversity at large and mostly related to mitigation or losses brought by climate change, particularly in forests or the soil biota. However, agrobiodiversity maintenance through use plays an important role for climate change adaptation. In the past, crop and livestock diversity has traditionally been an important part of farmer risk management. An increase of agrobiodiversity use is further expected and necessary as a result of climate change.

Agrobiodiversity at the gene, species and agroecosystem levels increases resilience to the changing climate. Promoting agrobiodiversity remains therefore crucial for local adaptation and resilience of agroecosystems (***FAO Interdepartmental Working Group on Climate Change and the Stockholm Environment Institute, 2007***). Adapting agriculture to climate change will indeed rely on matching crop cultivars to future climates and plant breeding for coping both with climate variability and extremes, but also on promoting farmer resilience and adaptability. Hence, agrobiodiversity is not a victim of climate change but provides the raw resource for adapting to this global challenge. The United Nations Environment Programme considers that breeding stress resistant crop cultivars, along with provision of crop and livestock insurance, social safety nets, new irrigation schemes and local management form the core of short-term responses for adapting to climate change (***UNEP, 2008***). Likewise, local agrobiodiversity is an important coping mechanism, especially for most vulnerable people. However, the locally available agrobiodiversity in some areas may not be able to adapt quickly to the changing climates. Hence, new crop cultivars, livestock breeds or other species better suited to these new environments will be needed to cope with climate change (***Lenné and Wood, 2011***).

2 *Climate Changes and Agriculture*

> ***Be*** the change you want to see in the world.
>
> *Mahatma Gandhi*

2.1 *Climate change: a blessing or a curse for agriculture*?

Global climate change is a change in the long-term weather patterns that characterize the regions of the world. Scientists state unequivocally that the earth is warming. Natural climate variability alone cannot explain this trend. Human activities, especially the burning of coal and oil, have warmed the earth by dramatically increasing the concentrations of heat-trapping gases in the atmosphere. The more of these gases humans put into the atmosphere, the more the earth will warm in the decades and centuries ahead. The impacts of warming can already be observed in many places, from rising sea levels to melting snow and ice to changing weather patterns. Climate change is already affecting ecosystems, freshwater supplies, and human health. Although climate change cannot be avoided entirely, the most severe impacts of climate change can be avoided by substantially reducing the amount of heat-trapping gases released into the atmosphere. However, the time available for beginning serious action to avoid severe global consequences is growing short. Global Warming or climate change is a topic that increasingly occupies the attention of the world. Is it really happening? If so, how much of it is due to human activities? How far will it be possible to adapt to changes of climate? What action to combat it can or should we take? How much will it cost? Or is it already too late for useful action? Why carbon dioxide is both a blessing and a curse? Is *climate change: a blessing or a curse for agriculture*? This book sets out to provide answers to all these questions by providing the best and latest information available.

Carbon dioxide might be a greenhouse gas, but it’s not necessarily bad for the planet. Without it, there’d be no plant life and no human life as we know it. It’s only toxic in high concentrations. And now the most important question is: is the climate changing? It could be answered this question as follows: It seems certain that the world will be even more crowded and more connected. Will the increasing scale of human activities affect the environment? In particular, will the world be warmer? How is its climate likely to change?

Variations in day-to-day weather are occurring all the time; they are very much part of our lives. The climate of a region is its average weather over a period that may be a few months, a season or a few years. Variations in climate are also very familiar to us. We describe summers as wet or dry, winters as mild, cold or stormy. In many parts of the world, no season is the same as the last or indeed the same as any previous season, nor will it be repeated in detail next time round. Most of these variations we take for granted; they add a lot of interest to our lives. Those we particularly notice are the extreme situations and the climate disasters. Most of the worst disasters in the world are, in fact, weather- or climate related.

Not all the climate changes will in the end be adverse. While some parts of the world experience more frequent or more severe droughts, floods or significant sea level rise, in other places crop yields may increase due to the fertilizing effect of carbon dioxide. Other places, perhaps for instance in the sub-arctic, may become more habitable. Even there, though, the likely rate of change will cause problems: large damage to buildings will occur in regions of melting permafrost, and trees in sub-arctic forests like trees elsewhere will not have time to adapt to new climatic regimes. Scientists are confident about the fact of global warming and climate change due to human activities. However, uncertainty remains about just how large the warming will be and what will be the patterns of change in different parts of the world. Although useful indications can be given, scientists cannot yet say in precise detail which regions will be most affected. Intensive research is needed to improve the confidence in scientific predictions (***Houghton, 2009***).

Climate change is an increasingly urgent problem with potentially far-reaching consequences for life on earth. Humans and wildlife are also exposed to an array of chemical, physical, and biological stressors that arise largely from anthropogenic activity, but also from natural sources. One of the consequences of climate change that has recently attracted attention is its potential to alter the environmental distribution and biological effects of chemical toxicants. There is growing awareness of the importance of anticipating the effects of chemical pollution in the rapidly changing environment, and identifying and mitigating effects in those humans and ecosystems most vulnerable (***Noyes et al. 2009***).

Today, global climate change is a fact. The climate has changed visibly, tangibly, measurably. An additional increase in average temperatures is not only possible, but very probable, while human intervention in the natural climate system plays an important, if not decisive role (***Porro, 2002***). Climate change is a major concern in relation to the minerals sector and sustainable development. It is, potentially, one of the greatest of all threats to the environment, to biodiversity and ultimately to our quality of life (***FTF, 2002***).

Climate on Earth has changed many times during the existence of our planet, ranging from the ice ages to periods of warmth. During the last several decades increases in average air temperatures have been reported and associated effects on climate have been debated worldwide in a variety of forums. Due to its importance around the globe, agriculture was one of the first sectors to be studied in terms of potential impacts of climate change (***Adams et al. 1990***). According to studies carried out by the Intergovernmental Panel on Climate Change (IPCC), average air temperatures will increase between 1.4 and 5.8 °C by the end of this century, based upon modeling techniques that incorporated data from ocean and atmospheric behavior (***IPCC, 2001***). The possible impacts of this study, however, are uncertain since processes such as heat, carbon, and radiation exchange among different ecosystems are still under investigation. Less drastic estimates predict temperature increase rates of 0.088 °C per decade for this century (***Kalnay and Cai, 2003***). Other investigators forecast for the near future that rising air temperature could induce more frequent occurrence of extreme drought, flooding or heat waves than in the past (***Assad et al. 2004***).

What climate changes are likely? Links between various elements of the climate system, illustrating how changes in any one can interact with others to produce positive or negative feedback effects. These and related phenomena can all interact to accelerate and reinforce climate change, as is illustrated in **Figure 2.1** (***Pittock, 2009***).

Climate change impacts are complex in that they can be both direct and indirect. For example, more rain may lead directly to either greater or smaller crop yields, depending on factors such as the type of crop, the soil and the present climate. Indirect effects could include changes in supply and demand as a result of these larger or smaller yields, both regionally and globally, and the resulting changes in commodity prices, the profitability of farming, and the affordability of food and effects on human health. Moreover, impacts can often be made more favorable by changing strategies so as to minimize losses and maximize gains. This is called adaptation.

Studies of specific local impacts of climate changes have been conducted by hundreds of research groups, many from organizations concerned with such matters as seasonal crop forecasts, water supply and coastal protection. These groups have found that climate change and sea-level rise of the magnitude and rates suggested would greatly affect many natural systems like forests, rivers and wildlife, as well as human activities and society. Examples include: (1) changes in natural productivity and biodiversity, with an increased rate of extinctions, (2) decreases in cereal crop yields in most tropical and sub-tropical countries, and in temperate countries for large warmings, (3) increased water shortages in many water-scarce regions due to regional decreases in precipitation, increased evaporation and loss of glaciers and seasonal snow storages, (4) adverse economic effects in many developing countries for even small warmings, and for developed countries for larger warmings, (5) tens of million of people on small islands and low-lying coastal areas at severe risk of flooding from sea-level rise and storm surges, (6) increased threats to human health, (7) increased inequities between poor and richer countries, (8) increased risk of abrupt and irreversible climate changes (***Pittock, 2009***).

It is intended to answer, in readily understood terms, frequently asked questions about climate change, such as: (1) what is the relationship between natural climate variations and human-induced climate change? (2) What are the major concerns regarding climate change? (3) Why are these arguments about the reality of climate change, and its policy implications? (4) How does climate change relate to other problems like population growth, poverty, pollution and land degradation? (5) How urgent is the problem? What can we about it, and how much will it cost?

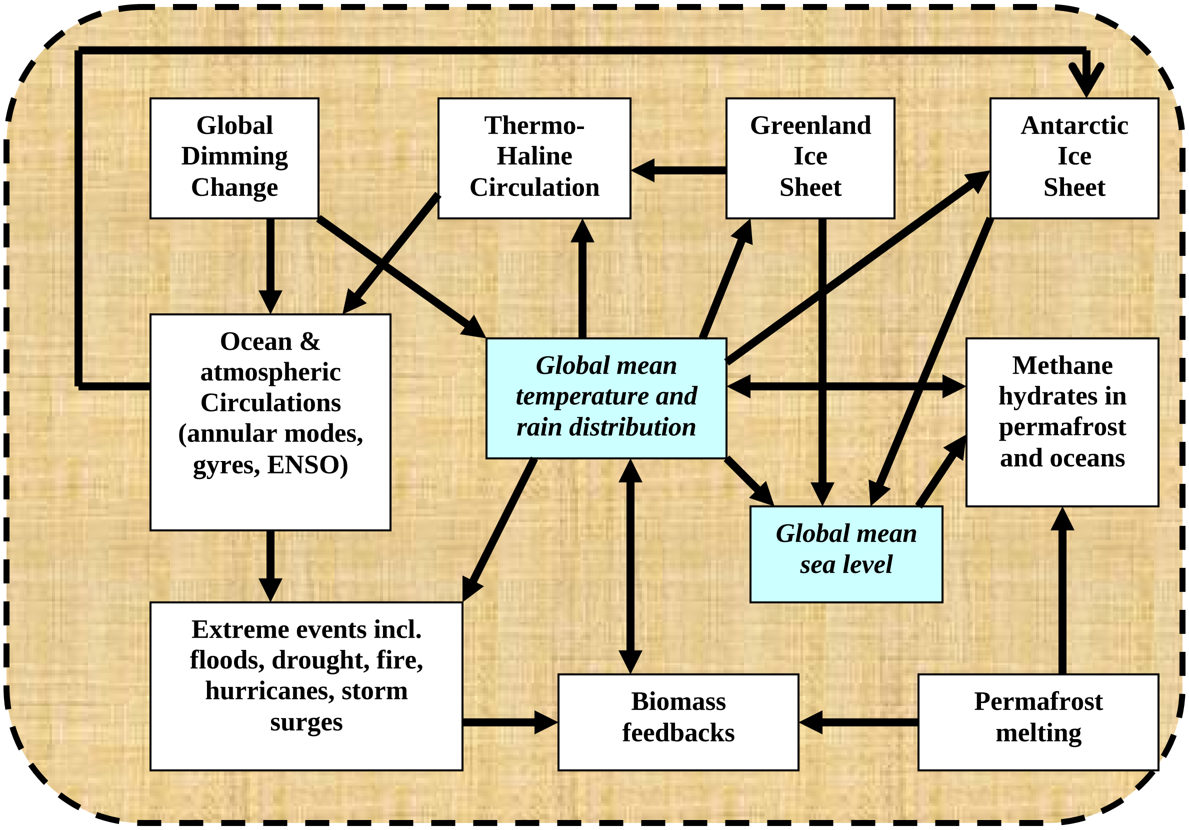


Figure 2.1: Links between various elements of the climate system, illustrating how changes in any one can interact with others to produce positive or negative feedback effects (adapted from ***Pittock, 2009***)

This chapter highlights the interactive effects of climate change, agriculture, and agricultural practices on global food security. The chapter focuses on global crop physiology and productivity, food production and safety, bioenergy and biodiversity and human rights and ethics on land use and soil management options that can enhance the SOC pool, thereby reducing the rate of enrichment of atmospheric CO_2 and improving food production by enhancing soil quality.

2.2 *Climate Changes and Agriculture*

In fact, climate is a primary determinant of agricultural productivity. In turn, food and fiber production is essential for sustaining and enhancing human welfare. Hence, agriculture has been a major concern in the discussions on climate change. Food supply vulnerability to climate change is an issue in two different ways. First, future food supply may be directly threatened by climate change. Second, food supply capacity may be altered by efforts to reduce GHGE as society tries to mitigate future implications of climate change. Agronomic and economic impacts from climate change depend primarily on two factors: (1) the rate and magnitude of change in climate attributes and the agricultural effects of these changes, and (2) the ability of agricultural production to adapt to changing environmental conditions (***McCarl et al. 2001***).

Temperature, precipitation, atmospheric carbon dioxide content, the incidence of extreme events and sea level rise are the main climate change related drivers which impact agricultural production. The main agricultural productivity implications of these drivers are indicated in **Table 2.1**.

Table 2.1: Types of impacts on agricultural production and markets (adapted from ***McCarl et al. 2001***)

Item subject to impact	**Type of Effect**				
	Temperature	**Precipitation**	**CO_2**	**Extreme Events**	**Sea Level**
Crops and Forages					
Plant Size - yield	X	X	X	X	
Water requirement	X		X		
Soils					
Soil Moisture	X	X		X	
Soil fertility	X	X			
Livestock					
Rate of gain	X			X	
Feed use	X			X	
Milk production	X			X	
Fertility	X			X	
Carrying Capacity	X	X	X	X	
Irrigation water supply					
Quantity	X	X		X	
Seasonality of supply	X				
Non agricultural competition	X	X		X	
Other					
Navigation	X		X		X
Low lying land inundation				X	X
Weed Competition	X	X	X		
Insects, fungus, diseases	X	X			

2.2.1 *Introduction*

Climate is the single most important determinant of agricultural productivity, primarily through its effects on temperature and water regimes. For example, the physiographic boundaries of principal biomes are determined by mean annual temperature and soil water regimes. Climate change is therefore expected to alter the biophysical environment of growing crops and to influence biomass productivity and agronomic yields (***Rosenzweig and Hillel, 1998***).

Positive effects may be associated with the fertilization effects of CO_2 enrichment, increases in the duration of growing seasons in higher latitudes and montane ecosystems, and possible increase in soil water availability in regions with an increase in annual precipitation. Each 1°C increase in temperature may lead to a 10-day increase in the growing season in northern Europe and Canada.

The CO_2 fertilization effect is real. However, the net positive effect may be moderated by other factors, such as the effective rooting depth and nutrient availability. Further, the productivity per unit of available water is expected to rise by 20% to 40% (***van de Geijn and Goudriaan, 1996***).

Negative effects of projected climate change on agriculture may be due to increases in respiration rate as temperature rises with attendant decreases in net primary productivity (NPP); increases in the incidence of pests and diseases; shortening of the growing period in some areas; decrease in water availability as rainfall patterns change; poor vernalization; and increased risks of soil degradation caused by erosion and possible decline in SOC concentration. The yield of rice has been estimated to decrease by 9% for each 1°C increase in temperature. **Phillips et al. (1996)**, using the explicit planetary isentropic coordinate (EPIC) model to examine the sensitivity of corn and soybean yields to climate change, projected a 3% decrease in both corn and soybean yields in response to a 2°C increase in temperature from a baseline precipitation level. However, a 10% precipitation increase balanced the negative effect of a 2°C temperature increase. The effects of climate change on crop yields may be more negative at lower latitudes and generally positive at middle and high-middle latitudes. Further, crop growth is more affected by extremes of weather than by averages. The annual average changes in temperature or precipitation used in most predictive models do not reflect the short-term effects of so-called extreme events — droughts, floods, freezes, or heat waves (***Lal, 2005***).

But the question must be asked: how remarkable are these extreme events that I have been listing? Do they point to a changing climate due to human activities? Here a note of caution must be sounded. The range of normal natural climate variation is large. Climate extremes are nothing new. Climate records are continually being broken. In fact, a month without a broken record somewhere would itself be something of a record!

But what is global warming? **Sir Houghton (2009)**, in his splendid book about *the global warming*, stated that, because carbon dioxide is a good absorber of heat radiation coming from the Earth's surface, increased carbon dioxide acts like a blanket over the surface, keeping it warmer than it would otherwise be. With the increased temperature the amount of water vapor in the atmosphere also increases, providing more blanketing and causing it to be even warmer. The gas methane is also increasing because of different human activities, for instance mining and agriculture, and adding to the problem. Being kept warmer may sound appealing to those of us who live in cool climates. However, an increase in global temperature will lead to global climate change. If the change were small and occurred slowly enough we would almost certainly be able to adapt to it. However, with rapid expansion taking place in the world's industry the change is unlikely to be either small or slow. **Houghton** presented that, in the absence of efforts to curb the rise in the emissions of carbon dioxide, the global average temperature will rise by about a third of a degree Celsius or more every ten years –

or three or more degrees in a century. This may not sound very much, especially when it is compared with normal temperature variations from day to night or between one day and the next. But it is not the temperature at one place but the temperature averaged over the whole globe. The predicted rate of change of 3 °C a century is probably faster than the global average temperature has changed at any time over the past 10 000 years. And as there is a difference in global average temperature of only about five or six degrees between the coldest part of an ice age and the warm periods in between ice ages, we can see that a few degrees in this global average can represent a big change in climate. It is to this change and especially to the very rapid rate of change that many ecosystems and human communities (especially those in developing countries) will find it difficult to adapt.

2.2.2 *Climate Prediction and Agriculture*

It is well established that, agricultural production is highly dependent on weather, climate and water availability, and is adversely affected by weather- and climate-related disasters. Failure of rains and occurrence of natural disasters such as floods and droughts could lead to crop failures, food insecurity, famine, loss of property and life, mass migration, and negative national economic growth. Hence, agricultural communities around the world have always looked for ways and means to cope with the climate variability including the use of various traditional indicators to predict the seasonal climate behavior.

In past two decades, significant advances have been made in the science and applications of seasonal climate forecasting. The principal scientific basis of seasonal forecasting is founded on the premise that lower-boundary forcing, which evolves on a slower timescale than that of the weather systems themselves, can give rise to significant predictability of atmospheric developments. These boundary conditions include sea surface temperature (SST), sea-ice cover and temperature, land-surface temperature and albedo, soil moisture and snow cover, although they are not all believed to be generally of equal importance. Climate variations, also called anomalies, are differences in the state of the climate system from normal conditions (averaged over many years, usually a 30-year period) for that time of the year. The strongest evidence for long-term predictability comes largely from the influence of persistent SST anomalies on the atmospheric circulation which, in turn, induces seasonal climate anomalies (***Sivakumar and Hansen, 2007***).

The key weather variables for crop prediction are rainfall, temperature and solar radiation, with humidity and wind speed playing also a role. As **Doblas-Reyes et al. (2006)** explained, seasonal climate forecasts are able to provide insight into the future climate evolution on timescales of seasons and longer because slowly-evolving variability in the oceans significantly influences variations in weather statistics. The climate forecast community is now capable of providing an end-to-end multi-scale (in space and time) integrated prediction system that provides skilful, useful predictions of variables with socio-economic interest. **Doblas-Reyes et al. (2006)** emphasize the importance of a fully probabilistic approach during all the stages of the forecasting process. Predictions of the climate system evolution in seasonal timescales suffer mainly from two sources of uncertainty: initial condition and structural model uncertainty. To address the first source of uncertainty, forecast models are run many times from slightly different initial conditions, consistent with the error to estimate the effect of this initial condition uncertainty. One way to represent model uncertainty is to incorporate, within the ensemble, independently derived models, resulting in a multi-model ensemble system (***Palmer et al. 2004***).

For agriculture, climate forecasts must be interpreted in terms of production outcomes at the scale of decisions if farmers and other agricultural decision-makers are to benefit. Interest in linking seasonal climate forecasts from general circulation models (GCMs) with crop models is motivated by: (*a*) the need for information that is directly relevant to decisions, (*b*) use for *ex ante* assessment of potential benefits to enhance credibility and support targeting, and (*c*) support for fostering and guiding management responses to advance climate information (***Hansen, 2005***).

Several avenues are likely to enhance the quality of forecasts of agricultural impacts of climate variations over the next five to ten years. First, dynamically coupling crop models within climate models will support refined two-way interaction between the atmosphere and agricultural land use. Second, remote sensing and proliferation of spatial environmental databases provide substantial opportunities to expand the use and enhance the quality and resolution of climate-based crop forecasts. Finally, climate-based crop forecasts will benefit from climate research in the emerging area of "weather within climate" (***Sivakumar and Hansen, 2007***).

The IPCC TAR (2001) provided a baseline for the prediction of climatic changes at broad scales by using historical measurements and future predictions made by several global circulation models (GCMs) in addition to what the first and second assessment reports had previously outlined (**IPCC, 1990, 1995**), but included the definitions of more politically oriented scenarios (i.e. the Special Report on Emissions Scenarios (SRES) scenarios; **IPCC, 2000**) rather than the IS92 emission scenarios described in the first and second assessment reports. Working group I (WGI) reported:

- Average diurnal temperature had increased by 0.6°C in the 20th century, with a significant increase from 1910 to 1945, followed by a slight decrease during the period 1945–1965, and a severe increase from 1976 to 2000;
- Increases in sea level between 0.1 and 0.2 m;
- Geographically differentiated increases and decreases in precipitation of at least 1% per decade;

- Increases in frequency and intensity of heavy rainfall events, increase in cloud cover; and
- Reductions in low temperature extreme events and increases in high temperature extreme events such as El Niño-Southern Oscillation (ENSO) (***Jarvis et al. 2010***).

The use of climate model results to assess the impacts of climate change on crop yields and agriculture in general began in the mid-1980s (e.g., ***Rosenzweig, 1985***). For the first 10 to fifteen years of this research, the downscaling method used was the simple "delta" method based on results from doubled CO_2 experiments. Initially, climate models did not include complete three-dimensional ocean models. Instead very simple "swamp" oceans were used, and trials were conducted for a control period, and then for a future period by doubling the concentrations of CO_2 in the models. With the simple ocean models, the simulations of future climate would soon reach equilibrium (i.e., become stable). Fully-coupled atmosphere-ocean global climate models (GCMs) did not come into use until the 1990s and were then capable of producing time-evolving responses to increasing CO_2 and other greenhouse gases (***Le Treut et al. 2007***). Changes in climate from one or more global climate models were appended to point observations of the variables needed in either deterministic or statistical crop yield models (e.g., ***Rosenzweig, 1985***). In this earlier period, usually only results from a few doubled CO_2 experiments were used, and the uncertainty was presented in the comparison of changes in yields based on the different future climates (***Mearns, 2011***).

Over time as the resolution of global climate models improved, more and more processes were included (three-dimensional oceans, land surface packages, explicit simulation of interactions with aerosols in the atmosphere), and longer simulations were produced (***Le Treut et al. 2007***). The availability of downscaling techniques further influenced the formation of climate scenarios for use in agricultural impacts (e.g., ***Thomson et al. 2002***). Early research on the effect of statistical and dynamical downscaling on calculations of climate effects on agriculture demonstrated that different changes in yield resulted from whether the large-scale or higher-resolution climate changes were used. **Olesen *et al.* (2007)** determined that the uncertainty in changes in crop yields was greater across the global models used in PRUDENCE (climate change model in Europe) than across the regional model simulated climate changes. For example, **Morse *et al.* (2009)** reported use of probability density functions developed with the ENSEMBLES simulations to calculated risks of wheat yield shortfalls in the Mediterranean region and probabilities of yield changes and nitrogen leaching in Denmark and Portugal (***Mearns, 2011***).

2.2.3 *Climate Changes and its Impact on Agriculture*

Driven mainly by population and economic growth, total world food consumption is expected to increase over 50% by 2030 and may double by 2050 (***Barker et al. 2007***). Most of the increase in food production in the next decades is expected to occur through further intensification of current cropping systems rather than through opening of new land into agricultural production. Intensification of cropping systems has been a highly successful strategy for increasing food production. The best example is the well-known success of the *Green Revolution*, where the adoption of modern varieties, irrigation, fertilizers and agrochemicals resulted in dramatic increases in food production. However, this strategy also resulted in unexpected environmental consequences, one of them being the emissions of greenhouse gases (GHGs) into the atmosphere. Therefore, future strategies that promote further intensification of agriculture should aim at the development of sustainable cropping systems that not only consider increasing food production but that also look at minimizing environmental impact (***Ortiz-Monasterio et al. 2010***).

At present, 40% of the Earth's land surface is managed for cropland and pasture (***Foley et al. 2005***). The most important cropping systems globally, in terms of meeting future food demand, are those based on the staple crops, *rice, wheat and maize*. Rice and maize are each grown on more than 155 million ha (***FAOSTAT, 2009***). In addition, rice is the staple food of the largest number of people on Earth. The geographic distribution of rice production gives particular significance to Asia where 90% of the world's rice is produced and consumed. Maize is produced mainly in the Americas, followed by Asia and then Africa. Maize is important as a staple crop (mainly in developing countries) but it is also important as animal feed and, increasingly, as biofuel. Wheat is the most widely grown crop, covering more than 215 million ha around the world, with Asia covering close to 50% of the world wheat area (***FAOSTAT, 2009***).

Without additional policies, agricultural N_2O and CH_4 emissions are projected to increase by 35–60% and ~60%, respectively, to 2030, thus increasing more rapidly than the 14% increase of non-CO_2 GHG observed from 1990 to 2005 (***Barker et al. 2007***). Improved agricultural management enhances resource-use efficiencies, often reducing emissions of more than one GHG. The effectiveness of these practices depends on factors such as climate, soil type and farming system. About 90% of the total mitigation arises from sink enhancement (soil C sequestration) and about 10% from emission reduction. The most prominent mitigation options in agriculture are shown in **Table 2.2**. In spite of inherent uncertainties in such estimates, it can be concluded that the topic of this review, which addresses the second option (improved cropland management) and the fifth option (improved rice management), comprises a sizable portion of the overall mitigation potential of agriculture (***Ortiz-Monasterio et al. 2010***).

Promoting agricultural practices that mitigate climate change by reducing GHG emissions is important, but those same practices also have to improve farmer production and income and buffer the production system against the effects of changes in climate. The overall impact predicted by climate change models vary but we are now locked into global warming and inevitable changes to climatic pattern that are likely to exacerbate existing rainfall variability and further increase the frequency of climatic extremes. Where excess rain occurs, extreme rainfall events will increase leading to flooding and soil erosion. In low rainfall, drought-prone areas there is general acceptance in the science community of more frequent moisture stress because of failed rainfall patterns and increased evaporation caused by higher temperatures (***Cooper et al. 2008***). In Africa specifically, the projected combined impacts of climate change and population growth suggest an alarming increase in water scarcity for many countries, with 22 of the 28 countries considered likely to face water scarcity or water stress by 2025. This in turn will curtail the ability of irrigated agriculture to respond to the expanding food requirements of tomorrow's Africa. This raises the spectre of a worsening food security crisis (***Rosegrant et al. 2002***).

In order to cope with the increased climate risk, agricultural systems will have to be more robust and resilient to buffer for extreme weather events such as drought, flooding, etc. It is paramount that new agricultural practices not only prevent further soil degradation but also improve system resilience through increased soil organic matter, improved water-use efficiency as well as nutrient-use efficiency, and increased flora and fauna biodiversity. However, the management of agriculture to cope with GHG emissions and the negative effects of climate change on food production lies in the hands of farmers, pastoralists and forest managers whose decisions are determined by multiple goals (***Hobbs and Govaerts, 2010***).

Table 2.2: Assessing mitigation potentials in agriculture (adapted from ***Barker et al. 2007***)

Mitigation option	**Million t CO_2-eq/year** [a]
Restoration of cultivated organic soils	1260
Improved cropland management (including agronomy, nutrient management, tillage/ residue management) and water management (including irrigation and drainage) and set-aside/agroforestry	1110
Improved grazing land management (including grazing intensity, increased productivity, nutrient management, fire management and species introduction)	810
Restoration of degraded lands (using erosion control, organic amendments and nutrient amendments)	690
Improved rice management	210
Improved livestock management (including improved feeding practices, dietary additives, breeding and other structural changes) and improved manure management (improved storage and handling and anaerobic digestion)	260

[a] Assuming C prices up to US$100/t CO_2-eq by 2030.

The impacts of climate change on agriculture are expected to be widespread across the globe, although studies suggest that African agriculture is likely to be most affected due to heavy reliance on low-input rainfed agriculture and due to its low adaptive capacity (***Mertz et al., 2009***). Broadly speaking, climate change is likely to impact crop productivity directly through changes in the growing environment, but also indirectly through shifts in the geography and prevalence of agricultural pests and diseases, associated impacts on soil fertility and biological function, and associated agricultural biodiversity. While many impact predictions tend towards the negative, increased CO_2 will also contribute to enhanced fertilization – although there is significant debate as to the extent to which this may increase plant growth. This section looks at these issues, concentrating entirely on the expected biophysical impacts (***Jarvis et al. 2010***).

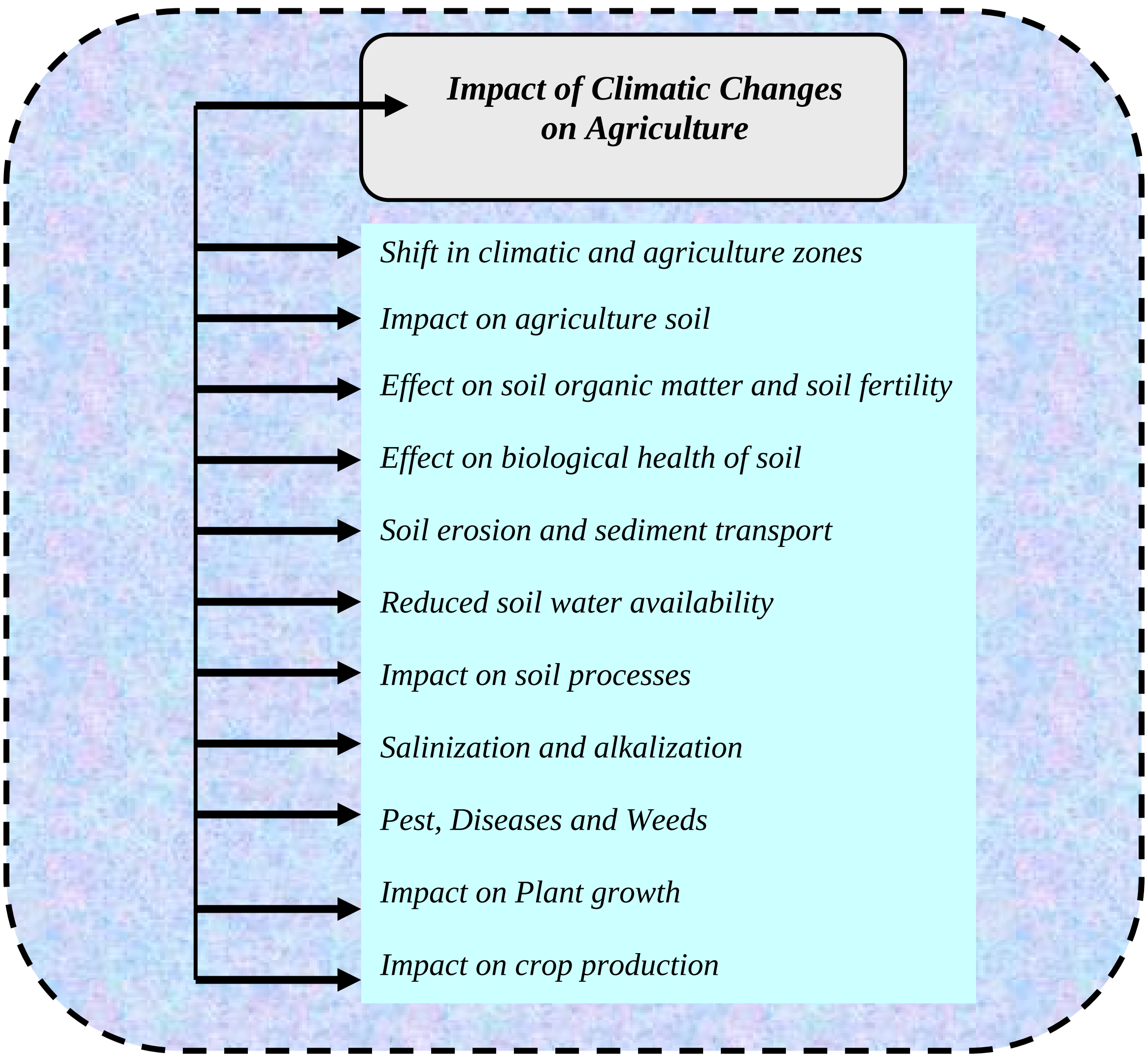


Figure 2.2: Points that must be considered while doing the study of impacts of climatic changes on agriculture (adapted from ***Khan et al. 2009c***)

Climate change due to anthropogenically-generated greenhouse gases and aerosols has been recognized as a serious threat to the earth's ecosystems and its inhabitants, and the dangers associated with climate change will increase in severity in coming decades in the absence of measures to curb the production of the responsible pollutants (e.g., carbon dioxide, methane, nitrous oxide). Numerous scientific articles and peer-reviewed reports have demonstrated the current and potential future effects of the climate change that result from these increased greenhouse gas emissions (***IPCC, 2007a***).

Among the resource sectors that received early attention regarding possible climate change effects has been agriculture and it has continued to receive considerable attention since that early research. Work in this area has become more sophisticated over time and is now connected explicitly to estimates of economics in the agricultural sector (***Reilly, 2010***) and risk of hunger. As is the case with many impact areas, studies of possible adaptation to climate change have come to the fore and become increasingly important (***Easterling, 2010***), and this is particularly striking for agriculture where studies of adaptation to climate change appeared early in the history of climate change research. The importance of adaptation studies has also put more emphasis on the need for more detailed information regarding future regional climate change (***Mearns, 2011***).

Mearns (2011) reviewed about the current and future climate change as follows:

Current climate change:

One of the most striking conclusions of the recent reports issued by IPCC (***IPCC, 2007b***) is that "most of the observed increase in global temperatures since the mid-20th century is very likely due to the observed increase in greenhouse gases in the atmosphere". The strength of this statement stands in stark contrast to the statement issued in the first IPCC report (***IPCC, 1990***) that "the observed increase (in temperature) could be largely due to natural variability". Global temperature has increased by about 0.75ºC from 1860 to 2005.

Evidence for the attribution of climate change to anthropogenically-generated greenhouse gases has steadily increased. Not only has temperature on global and regional scales increased, but other aspects of climate have also changed. These include increases in the amount of water vapor in the atmosphere, increases in global sea level (1.8 mm/year since the early 1960s), decreases in the extent of Arctic sea ice (7.4% per decade in summer), retreat of most glaciers, changes in precipitation amounts (both increases and decreases depending on the region), increases and decreases in ocean salinity, increased ocean acidity, and increased frequency of heavy precipitation events over most land areas (***IPCC, 2007b***). These tendencies are consistent with what one would expect to see under conditions of increased concentrations of greenhouse gases (***Mearns, 2011***).

***Future Climate*:**

Future climate (as well as some aspects of current and past climates) is studied mainly through the use of global climate models (GCMs). These are highly complex mathematical models that include representations of physical laws such as Newton's second law of motion, laws of conservation of mass and energy, laws of thermodynamics and the ideal gas law. The models represent important complex processes of the land surface, atmosphere, oceans and sea ice, as well as complex interactions among them (as shown in ***climate system figure***). Over the past 30 years or so, these models have advanced continuously in their complexity, spatial resolution and length of simulations partially due to the rapid, nonlinear increase in computer power (***Mearns, 2011***).

In order to estimate future climate changes, projections of the anticipated pathways of emissions of greenhouse gases and aerosols are generally made. Greenhouse gases in the atmosphere, such as CO_2, have very important effects on the energy balance of the earth-atmosphere system. They are relatively transparent to the energy coming from the sun, but they intercept the long wave energy that is emitted from the earth back out toward space. This is known as the greenhouse effect, and it is a natural part of the climate system. However, humans have been steadily increasing the amount of greenhouse gases emitted into the atmosphere. Thus, more and more energy is being trapped in the earth-atmosphere system. Estimating future emissions is a very difficult aspect of the climate change problem (***Mearns, 2011***).

In order to do so, one must also make projections of the socio-economic development of the entire world, including, for example, population growth, evolution of technology, the political and economic future, as well as whether we will manage to decrease (i.e., mitigate) the emissions of these gases. Under the auspices of the IPCC, a report was produced that presented a series of possible future pathways of greenhouse gases (i.e., CO_2, CH_4, and N_2O) and aerosols based on different scenarios about how the world might develop. It should be noted that agriculture (and associated changes in land use) is currently an important contributor to greenhouse gas emissions. It produces about 25% of CO_2 emissions (due to deforestation and oxidation of soil organic carbon), 50% of methane emissions (due to livestock and rice cultivation), and 75% of nitrous oxide emissions (primarily fertilizer application) (***Rosenzweig and Tubiello, 2007***).

In total, 40 different scenarios of emissions were produced, but these were grouped based on 4 different major story lines. The four story lines varied based on two major axes of future world development: one axis concerned the degree to which environmental sustainability or protection dominated versus the drive for economic growth, and the other concerned whether the world maintained a primarily global economic and political perspective or if the world became more dominated by regionally-oriented concerns. Embedded within these four different scenarios are assumptions about different rates of population growth, dominance of particular forms of energy (e.g., coal and oil versus renewable resources), and certain aspects of land use. The four scenarios were referred to as A1, B1, A2, and B2. The A1 scenario was divided into three subtypes (A1B, A1FI, A1T), and the resulting six scenarios are collectively referred to as the "representative" scenarios. **Table (2.3)** summarizes some major characteristics of these scenarios (***Mearns, 2011***).

Table 2.3: Characteristics of the representative SRES scenarios—values are for 2100 (adapted from ***Mearns, 2011***)

Scenario	Description	Population (billion)	Energy (Share of coal, %)	CO_2 (Gt/C/yr)	SO_2 (aerosols) (Mt S/yr)
A1FI	Rapid economic growth, rapid introduction of new technologies, but fossil fuel intensive	7.1	29	30.3	40
A2	Economic development regionally oriented— slow development of technology	15.1	53	28.9	60
A1B	Similar to A1FI, but more balanced energy portfolio	7.1	4 1	3.1	28
B2	Local solutions to economy, intermediate economic development, less rapid tech change compared to "1s"	10.4	22	13.8	48
B1	Service oriented economies, clean and efficient energy technologies	7.0	8	5.2	25
A1T	Similar to A1FI, but strong emphasis on clean technologies	7.0	1	4.3	20

2.2.4 *Climate change's impacts on global crop productivity*

The major concerns for crop productivity as a result of increased levels of greenhouse gases are related to warmer temperatures and altered amounts and patterns of rainfall. Both average temperature and temperature variability are predicted to increase. Average global temperatures are predicted to increase by 0.6–2.5°C over the next 50 years with significant spatial variation. While this will permit cultivation of crops in areas of the world which are currently too cold (e.g. Siberia and northern America) and extend the potential growing season for others, it will also threaten the viability of crops in many of the major areas of production. Simulation models suggest that wheat yields in south-east Australia may decrease by about 29% (***Anwar et al. 2007***) and direct studies in the Philippines have shown that irrigated rice yields decrease by 10% for each 1°C increase in the minimum night-time temperature although the maximum temperature has no effect (***Peng et al. 2004***).

Higher temperatures will shorten the life cycle of most crops, by accelerating development and hastening senescence, thereby decreasing the time available to harvest light and produce biomass. The effects on phenology vary both between species and with environment. Perennial crops may respond more strongly to an increased temperature than annual crops (***Estrella et al. 2007***). Other effects such as drought or an increase in ozone concentrations can exacerbate these effects. The decreased time available to harvest light and produce biomass contributes to yield reductions at elevated temperatures (***Parry and Hawkesford, 2010***).

Our knowledge of water use is as poor as our knowledge of water resources perhaps poorer. Information is largely incomplete particularly for agriculture, the largest user and is lacking altogether for some countries. Only limited disaggregated information exists, and even this shows deficiencies of validity and homogeneity and provides extremely poor information on trends. The quality of information systems varies with each country, but there are common difficulties: (1) Statistics on the magnitude of demand and withdrawal are often estimated rather than based on data that are measured or collected from censuses. The level of uncertainty varies, but is particularly high for agriculture. (2) Sectors of use are not defined homogeneously and are not well disaggregated. (3) Adequate historical datasets are rare, and the dates of available statistics are not always explicit. (4) Lack of agreed terminology leads to discrepancies in data compilation and analyses. Agriculture is by far the main user of water. Irrigated agriculture accounts for 70% of water withdrawals, which can rise to more than 80% in some regions (**Table 2.4**). Although increasing in urbanized economies, industrial (including energy) use accounts for only 20% of total water use and domestic use for about 10%. Water withdrawals for energy generation, hydropower and thermo-cooling are on the rise, but energy is one of the economic sectors that consumes the least water and it returns most of the water withdrawn back to the water system (about 95%). This is only a partial picture of sectoral usage as there are many unaccounted-for uses. Little is known about water use in informal urban settlements or informal irrigation systems, both of which are generally unaccounted for in official statistics (***Connor et al. 2009***).

Nowadays, climate changes, their causes and consequences, gained importance in many other areas of interest for sustainable life on Earth. The subject is, however, controversial. Understanding how climate changes will impact mankind in the decades to come is of paramount importance for our survival. Temperature, carbon dioxide (CO_2) and ozone (O_3) directly and indirectly affect the production and quality of fruit and vegetable crops grown in different climates around the world. Temperature variation can directly affect crop photosynthesis, and a rise in global temperatures can be expected to have significant impact on postharvest quality by altering important quality parameters such as synthesis of sugars, organic acids, antioxidant compounds and firmness. Rising levels of CO_2 also contribute to global warming, by entrapping heat in the atmosphere. Prolonged exposure to concentrations could induce higher incidences of tuber malformation and increased levels of sugars in potato and diminished protein and mineral contents, leading to loss of nutritional and sensory quality. Increased levels of O_3 in the atmosphere can lead to detrimental effects on postharvest quality of fruit and vegetable crops. Elevated levels of O_3 can induce visual injury and physiological disorders in different species, as well as significant changes in dry matter, reducing sugars, citric and malic acid, among other important quality parameters (***Moretti et al. 2010***).

Table 2.4: Water resources and withdrawals, 2000 (m^3 per year unless otherwise indicated, adapted from ***Connor et al. 2009***)

Region	Renewable water resources	Total water withdrawals	Water withdrawals						Withdrawals as percent of renewable resources
			Agriculture		Industry		Domestic (urban)		
			Amount	Percent	Amount	Percent	Amount	Percent	
Africa	3,936	217	186	86	9	4	22	10	5.5
Asia	11,594	2,378	1,936	81	270	11	172	7	20.5
Latin America	13,477	252	178	71	26	10	47	19	1.9
Caribbean	93	13	9	69	1	8	3	23	14.0
North America	6,253	525	203	39	252	48	70	13	8.4
Oceania	1,703	26	18	73	3	12	5	19	1.5
Europe	6,603	418	132	32	223	53	63	15	6.3
World	43,659	3,829	2,663	70	784	20	382	10	8.8

Note: *Water use* refers to water that is being put to beneficial use by humans. Detailed water accounting, however, requires more precise definition of terms.

Water withdrawal is the gross amount of water extracted from any source in the natural environment for human purposes. Differentiating withdrawals by type of source is useful to understand the pressure put on different parts of the system.

Water demand is the volume of water needed for a given activity. If supply is unconstrained, water demand is equal to water withdrawal.

Besides increase in temperature and its associated effects, climate changes are also a consequence of alterations in the composition of gaseous constituents in the atmosphere. CO_2, also known as the most important greenhouse gas, and O_3 concentrations in the atmosphere are changing during the last decade and are affecting many aspects of fruit and vegetable crops production around the globe (***Felzer et al. 2007***).

Exposure to elevated temperatures can cause morphological, anatomical, physiological, and, ultimately, biochemical changes in plant tissues and, as a consequence, can affect growth and development of different plant organs. These events can cause drastic reductions in commercial yield. However, by understanding plant tissues physiological responses to high temperatures, mechanisms of heat tolerances and possible strategies to improve yield, it is possible to predict reactions that will take place in the different steps of fruit and vegetable crops production, harvest and postharvest (***Kays, 1997***). Temperature increase and the effects of greenhouse gases are among the most important issues associated with climate change. Studies have shown that the production and quality of fresh fruit and vegetable crops can be directly and indirectly affected by high temperatures and exposure to elevated levels of carbon dioxide and ozone. Temperature increase affects photosynthesis directly, causing alterations in sugars, organic acids, and flavonoids contents, firmness and antioxidant activity. Higher temperatures can increase the capacity of air to absorb water vapor and, consequently, generate a higher demand for water. Higher evapotranspiration indices could lower or deplete the water reservoir in soils, creating water stress in plants during dry seasons. For example, water stress is of great concern in fruit production, because trees are not irrigated in many production areas around the world. It is well documented that water stress not only reduces crop productivity but also tends to accelerate fruit ripening (***Henson, 2008***).

Carbon dioxide concentrations are increasing in the atmosphere during the last decades (***Mearns, 2000***). The current atmospheric CO_2 concentration is higher than at any time in the past 420,000 years (***Petit et al. 1999***). Further increases due to anthropogenic activities have been predicted. Carbon dioxide concentrations are expected to be 100% higher in 2100 than the one observed at the pre-industrial era (***IPCC, 2007***). Ozone concentration in the atmosphere is also increasing. Even low-levels of ozone in the vicinities of big cities can cause visible injuries to plant tissues as well as physiological alterations (***Felzer et al. 2007***). Carbon dioxide accumulation in the atmosphere has directly effects on postharvest quality causing tuber malformation, occurrence of common scab, and changes in reducing sugars contents on potatoes. High concentrations of atmospheric ozone can potentially cause reduction in the photosynthetic process, growth and biomass accumulation. Ozone-enriched atmospheres increased vitamin C content and decreased emissions of volatile esters on strawberries. Tomatoes exposed to ozone concentrations ranging from 0.005 to 1.0 μ mol mol^{-1} had a transient increase in b-carotene, lutein and lycopene contents.

The above mentioned climate changes can potentially cause postharvest quality alterations in fruit and vegetable crops. Although many researchers have addressed climate changes in the past and, in some cases, focused postharvest alterations, the information is not organized and available for postharvest physiologists and food scientists that are interested in better understanding how these changes will affect their area of expertise (**Table 2.5; *Moretti et al. 2010***).

IPCC (2007) concluded that 'in mid- to high latitude regions, moderate warming benefits crop and pasture yields, but even slight warming decreases yields in seasonally dry and low-latitude regions (medium confidence)'. In IPCC language, moderate warming is in the range of 1–3°C. Smallholder and subsistence farmers, pastoralists and artisanal fisher-folk will suffer complex, localized impacts of climate change (high confidence). Food and forestry trades are projected to increase in response to climate change with increased dependence on food imports for most developing countries (medium to low confidence). The report further concluded that warming beyond 2–3°C was likely to result in yield declines in all areas. This analysis was based on a synthesis of 69 studies, which was a vast improvement on the handful of studies used in the TAR (***IPCC, 2001***).

But even since the IPCC FAR (2007) there has been a much larger number of studies which examine the impacts of climate change on crop production and yields, including global multi-crop studies, down to regional and national studies on individual crops. This chapter summarizes the IPCC findings, and provides a more detailed analysis of impact studies arising from 2006 to 2009. There are fairly consistent pictures drawn by different studies that show the potential effects of changing climates (***Lobell et al. 2008***). These all show steeply increasing trends in adverse impacts, particularly in food insecure regions among the tropics, which are likely to increase the extent to which these regions are food insecure, especially taking into account that most of these regions present the least adaptive capacity (***Jarvis et al. 2010***).

Grain yields are expected to fall in developing countries; however, the opposite is likely to happen in developed countries (***IPCC, 2007a***). Geographies of changes may influence yield responses: in high latitudes (where most of the developed countries are located), increased temperatures could increase the duration of growing seasons, thus benefiting farmers. However, in developing countries, which are mostly located in the tropics, this effect would not be observed. Investment capacity within the different agricultural sectors needs to be considered if yield losses are to be offset. Moreover, yield reductions will certainly result in increases in prices of agricultural goods, and this impact will be greater for food insecure regions (***Jarvis et al. 2010***).

2.2.5 *Impacts of climate changes on crop physiology*

Agriculture accounts for 70% of freshwater withdrawals from rivers, lakes and aquifers up to more than 90% in some developing countries. Furthermore, unlike in industrial and domestic uses, where most of the water returns to rivers after use, in agriculture a large part of water is consumed by evapotranspiration. Many irrigation systems, however, return a large amount of water to the system after use. Biomass cannot be produced without water. The source of all food is photosynthesis. Biomass is processed through the food chain, which describes the flow of energy and feeding relationship between species: from primary producers (plants) to herbivores to carnivores. It could be estimated how much water is needed to sustain our diets by calculating the water lost in evapotranspiration based on crop physiology. Depending on local climate, varieties and agronomical practices, it takes 400-2,000 litres of evapotranspiration daily to produce 1 kilogram (kg) of wheat, and 1,000 – 20,000 litres per kilogram of meat, depending on the type of animal, feed and management practices. Based on these values, researchers have estimated daily water requirements to support diets, ranging from 2,000 to 5,000 litres of water per person per day. FAO uses 2,800 kilocalories (kcal) per person at the national level as a threshold for food security. As a rule of thumb, it can therefore be estimated that 1 litre of water is needed to produce 1 kcal of food. Because of the low energy efficiency of the food chain, protein-rich diets require substantially more water than vegetarian diets (**Table 2.6**; ***Connor et al. 2009***).

Table 2.5: Physiological and quality parameters of fruit and vegetable crops affected by exposure to increased CO_2 levels (adapted from ***Moretti et al. 2010***)

Physiological or quality parameter	***Effect of high*** CO_2	***Product***	***Reference***
Photosynthesis	↑	Potato; spinach	Katnya et al. (2005), Jain et al. (2007)
Respiration	↓	Asparagus; broccoli; mungbean sprouts; blueberries; tomatoes; pears	Beaudry (1993), Peppelenbos and Leven (1996)
	↑	Potatoes; lettuce, eggplants; lemons; cucumbers; mango	Pal and Buescher (1993), Fonseca et al. (2002), Bender et al. (1994)
	=	Apples	Peppelenbos and Leven (1996)
Ripening	↓	Tomato	Klieber et al. (1996)
Stomatal conductance	↓	Spinach	Leakey et al. (2006), Jain et al. (2007)
Firmness	=	Tomato	Klieber et al. (1996)
	↑	Strawberry; raspberry	Siriphanich et al. (1998), Haffner et al. (2002)
Color intensity	↑	Grape	Bindi et al. (2001)
Dry matter	↑	Potato	Vorne et al. (2002)
Starch	↑	Potato	Vorne et al. (2002)
Alcohol	↑	Grape; mango; pear	Bindi et al. (2001), Bender et al. (1994)
Titratable Acidity	=	Grape	Bindi et al. (2001)
Citric Acid	↓	Potato; tomato	Donnelly et al. (2001), Islam et al. (1996)
Malic Acid	↓	Potato; tomato	Vorne et al. (2002), Islam et al. (1996)
Ascorbic acid	↑	Potato; strawberry; orange; tomato	Vorne et al. (2002), Wang et al. (2003), Idso et al. (2002), Islam et al. (1996)
Reducing sugars	↑	Potato	Vorne et al. (2002); Hoegy and Fangmeier (2009)
		Tomato	Islam et al. (1996)
Total phenolics	↑	Grape; strawberry	Bindi et al. (2001); Wang et al. (2003)
Flavonoids	↑	Grape	Bindi et al. (2001)
Anthocyanins	↑	Grape; strawberry	Bindi et al. (2001), Wang et al. (2003)
Glycoalkaloids	↓	Potato	Vorne et al. (2002)
pH	=	Grape	Bindi et al. (2001)
Nitrate	↓	Potato; celery; leaf lettuce; Chinese cabbage	Vorne et al. (2002), Jin et al. (2009)
Volatile compounds	↓	Mango	Lalel et al. (2003)
Antioxidant capacity	↓	Scallion; strawberry	Levinea and Paré (2009), Shin et al. (2008)

Over the past 800,000 years, atmospheric [CO_2] changed between 180 ppm (glacial periods) and 280 ppm (interglacial periods) as Earth moved between ice ages. From pre-industrial levels of 280 ppm, [CO_2] has increased steadily to 384 ppm in 2009, and mean temperature has increased by 0.76 °C over the same time period. Projections to the end of this century suggest that atmospheric [CO_2] will top 700 ppm or more, whereas global temperature will increase by 1.8–4.0 °C, depending on the greenhouse emission scenario (***IPCC, 2007***). There is growing evidence suggesting that many crops, notably C_3 crops, may respond positively to increased atmospheric CO_2 in the absence of other stressful conditions (***Long et al. 2004***), but the beneficial direct impact of elevated CO_2 can be offset by other effects of climate change, such as elevated temperatures, higher tropospheric ozone concentrations and altered patterns of precipitation (***Easterling et al. 2007; Da Matta et al. 2010***).

It is now universally accepted that increased atmospheric concentrations of ‘greenhouse gases’ are the main cause of the ongoing climate change (***Forster et al. 2007***) and that these changes are expected to have important effects on different economic sectors (e.g. agriculture, forestry, energy consumptions, tourism, etc.) (***Hanson et al. 2007***). Since agricultural practices are climate-dependent and yields vary from year to year depending on climate variability, the agricultural sector is particularly exposed to changes in climate. In Europe, the present climatic trend indicates that in the northern areas, climate change may primarily have positive effects through increases in productivity and in the range of species grown (***Alcamo et al. 2007***), while in southern areas (i.e. the Mediterranean basin) the disadvantages will predominate with lower harvestable yields, higher yield variability and a reduction in suitable areas for traditional crops (***Olesen and Bindi 2002; Moriondo et al. 2010***).

Table 2.6: Value produced from a unit of water for selected commodities (adapted from ***Connor et al. 2009***)

Product	**Water productivity**			
	Kilograms per cubic metre	Dollars per cubic metre	Protein grams per cubic metre	Kilocalories per cubic metre
Cereal				
Wheat ($ 0.2 per kilogram)	0.20 – 1.2	0.04 – 0.24	50 – 150	660 – 4,000
Rice ($ 0.31 per kilogram)	0.15 – 1.6	0.05 – 0.18	12 – 50	500 – 2,000
Maize ($ 0.11 per kilogram)	0.30 – 2.0	0.03 – 0.22	30 – 200	1,000 – 7,000
Legumes				
Lentils ($ 0.3 per kilogram)	0.3 – 1.0	0.09 – 0.30	90 – 150	1,060 – 3,500
Faba beans ($ 0.3 per kilogram)	0.3 – 0.8	0.09 – 0.24	100 – 150	1,260 – 3,360
Groundnut ($ 0.8 per kilogram)	0.1 – 0.4	0.08 – 0.32	30 – 120	800 – 3,200
Vegetables				
Potatoes ($ 0.1 per kilogram)	3 – 7	0.30 – 0.7	50 – 120	3,000 – 7,000
Tomatoes ($ 0.15 per kilogram)	5 – 20	0.75 – 3.0	50 – 200	1,000 – 4,000
Onions ($ 0.1 per kilogram)	3 – 10	0.30 – 1.0	20 – 67	1,200 – 4,000
Fruits				
Apples ($ 0.8 per kilogram)	1.0 – 5.0	0.8 – 4.0	Negligible	520 – 2,600
Olives ($ 1.0 per kilogram)	1.0 – 3.0	1.0 – 3.0	10 – 30	1,150 – 3,450
Dates ($ 2.0 per kilogram)	0.4 – 0.8	0.8 – 1.6	8 – 16	1,120 – 2,240
Others				
Beef ($3.0 per kilogram)	0.03 – 0.1	0.09 – 0.3	10 – 30	60 – 210
Fish (aquaculture[a])	0.05 – 1.0	0.07 – 1.35	17 – 340	85 – 1,750

[a] Includes extensive systems without additional nutritional inputs to super intensive systems.

For climate change impact assessment, crop growth models have been widely used to evaluate crop responses (development, growth and yield) by combining future climate conditions, obtained from General or Regional Circulation Models (GCMs and RCMs, respectively), with the simulation of CO_2 physiological effects, derived from crop experiments (***Ainsworth and Long 2005***). Many of these impact studies were aimed at assessing crop development shifts and yield variations under changes in mean climate conditions. These analyses showed that increasing temperatures generally shortened the growing period of commercial crops (e.g. ***Giannakopoulos et al. 2009***), resulting in a shorter time for biomass accumulation. On the other hand, changes in yields were not homogeneous and dependent on crop phenology (e.g. summer and winter crops), crop type (e.g. C_3 and C_4 plants) or environmental conditions (water and nutrient availability) (***Brassard and Singh 2008; Giannakopoulos et al. 2009; Moriondo et al. 2010***).

Other studies stressed that changes in climate variability, as can be expected in a warmer climate, may have a more profound effect on yield than changes in mean climate (***Porter and Semenov, 2005***). As such, policy analysis should not rely on scenarios of future climate involving only changes in means. Furthermore, the changes in the frequency of extreme climatic events during the more sensitive growth stages have been recognized as a major yield-determining factor for some regions in the future (e.g. ***Easterling and Apps 2005; Schneider et al. 2007***). Temperatures outside the range of those typically expected during the growing season may have severe consequences on crops, and when occurring during key development stages they may have a dramatic impact on final production, even in case of generally favorable weather conditions for the rest of the growing season. Many studies highlighted the potential of heat stresses during the anthesis stage as a yield reducing factor (***Challinor et al. 2005***), while others pointed out that the joint probability of heat stress-anthesis is likely to increase in future scenarios (***Alcamo et al. 2007***). Accordingly, both changes in mean climate and climate variability (including extreme events) should be considered for a reliable climate change impact assessment in agriculture. An example is the summer heat wave of 2003 (***Schaer et al. 2004***), taken as an indicator of the future climate change, which reduced cereal production in Europe by 23 MT with respect to 2002. The reason for this reduction was attributed to the shorter growing season combined with a higher frequency of extreme events, both in terms of maximum temperatures and longer dry spells (***Olesen and Bindi 2004***). In contrast, climate change impact assessments carried out so far have not included direct simulations of heat stress impact on crop yield (***Schneider et al. 2007***) resulting in a probable underestimation of yield losses **(*Moriondo et al. 2010*).**

The temperature response of crop growth and yield must be considered to predict the [CO_2] effects. The threshold developmental responses of crops to temperature are often well defined, changing direction over a narrow temperature (***Porter and Semenov, 2005***). High temperatures reduce the net carbon gain in C_3

species by increasing photorespiration; by reducing photorespiration, [CO_2] enrichment is expected to increase photosynthesis more at high than at low temperatures, and thus at least partially offsetting the temperature effects of supra-optimal temperatures on yield (***Polley, 2002***). Therefore, yield increases at high [CO_2] should occur most frequently in regions where temperatures approximate the optimum for crop growth. Conversely, in regions where high temperatures already are severely limiting, further increases in temperature will depress crop yield regardless of changes in [CO_2] (***Polley, 2002***). In fact, results of mathematical modeling suggest that, in mid- to high-latitude regions, moderate to medium local increases in temperature (1–3 °C), along with associated CO_2 increase and rainfall changes, can have beneficial impacts on crop yields, but in low-latitude regions even moderate temperature increases (1–2 °C) are likely to have negative impacts on yield of major cereals (***Easterling et al. 2007***). Thus, climate change may impair food production, particularly in developing countries, most of which are located in tropical regions with warmer baseline climates (***Tubiello and Fischer, 2007; Da Matta et al. 2010***).

In addition to crop growth and yield, crop quality is also expected to be affected by global climatic changes. Crop quality is thought to be a multi-faceted and complex subject involving growth, assimilate partitioning and storage, and pre- and post-harvest, including nutritional, technological and environmental facets (***Hay and Porter, 2006***). Elemental (e.g., zinc, iodine) and macromolecular (e.g., protein) composition in plant tissues are expected to change in a future high-CO_2 world (***Taub et al. 2008***). In this context, crop physiologists will need to take more account of the interests of breeders and processors by studying, quantifying and modeling the differences not only in increasing yields but also in food quality among crop varieties and species in climate change scenarios (***Hay and Porter, 2006***). The efforts to understand the impact of elevated [CO_2], temperature and other ongoing climatic changes on food crops are crucial to estimate food production in the future. The present review, which is by no means exhaustive, is mainly focused on the current understanding of the consequences of climatic changes (mainly CO_2 enrichment and temperature) on crop physiology and chemistry (***Da Matta et al. 2010***).

Crops sense and respond directly to rising [CO_2] through photosynthesis and stomatal conductance, and this is the basis for the CO_2 fertilization effect on crop yield (***Long et al. 2006***). These responses are highly dependent on temperature (***Polley, 2002***). Therefore, understanding how crop species will respond to these environmental changes is crucial for maximizing the potential benefits of elevated CO_2, for which agronomic practice needs to adapt as both temperature and CO_2 rise (***Challinor and Wheeler, 2008***). In fact, both chemical and microbiological risks are foreseen to impair food and feed safety as a consequence of climate change: in particular, mycotoxins, pesticide residues, trace metals and other chemicals could affect food and feed safety (***Miraglia et al. 2009***). There is, therefore, an urgent need for scientific research that can improve our understanding of the interactions of rising atmospheric [CO_2] with other environmental variables, such as temperature, water supply and ozone concentration, as well as with biotic factors such as pests and diseases, under real field conditions. In doing so, it is necessary not only to quantify the effects of climatic changes on crop production but also on food quality. It is also necessary to assess responses of crops other than the key cereal grains, and in climate regions other than temperate ones, notably those of importance to developing countries in the tropics and subtropics (***Tubiello et al. 2007***). Furthermore, since distinct varieties seem to respond differently to elevated CO_2 and temperature in terms of harvestable yield, future research should be also directed towards selecting promising genotypes for a changing global climate (***Da Matta et al. 2010***).

2.2.6 *Impacts of climate changes on food production and safety*

One-sixth of the world's human population has insufficient food to sustain life, and food supply will need to double by 2050 to meet this demand. Agricultural genetics is one of the components of the solution to meet this challenge. The most serious challenges economies and societies will face over the next decades include providing food and the water needed for food production, to a world that will see its population increase by a third in the face of mounting environmental stresses, worsened by the consequences of global climate change.

The challenge of increasing food production in the face of climate change will be greatest for the production of the staple grain crops that form the basis of diets the world over. Wheat, maize and rice are the three major staples, covering together 40% of the global crop land of 1.4 billion ha (***FAOSTAT, 2009***). Together they provide 37% of all protein, and 44% of all calories for human consumption (**Table 2.7**). Each crop provides more than 50% of the daily caloric uptake in regions with high consumption, for example North Africa and Central Asia for wheat, sub-Saharan African countries and mesoamerican countries for maize, and South and Eastern Asian countries for rice, and especially among the poorest people in these regions. Wheat is, with 220 million ha, the most widely grown crop followed by maize with 158 million ha and rice with 155 million ha. Average yield of maize, rice and wheat is 5, 3.9 and 3 t/ha, respectively (***Braun et al. 2010***).

Although around 135 countries produce more than 10,000 t of maize compared with 100 countries that produce more than 10,000 t of wheat, wheat shows the widest geographical distribution because it is grown from Ecuador to 67°N in Scandinavia to 45°S in Argentina, Chile and New Zealand. Maize is grown from 55°N in Western Europe to 45°S in New Zealand. Rice is grown in a narrower geographic belt between 40°N in Japan and 30°S in Brazil, but is grown over a very wide range of hydrological environments within this area (***Braun et al. 2010***).

Table 2.7: Percentage of calories and protein in the human diet obtained from wheat, maize and rice globally and in the developing world (adapted from ***FAOSTAT, 2009***)

Grain crop	Region	Calories (%)	Protein (%)
Maize	World	5	4
	Developing countries	6	5
Wheat	World	19	20
	Developing countries	17	19
Rice	World	20	13
	Developing countries	25	18
Total from wheat, rice and maize	World	44	37
	Developing countries	48	42

There are many factors that affect food safety such as global trade, socio-economic and technological development, urbanization and agricultural land use. Climate change and variability are among the multiple factors that can provoke changes in the nature and occurrence of food safety hazards. These hazards can arise at various stages of the food chain, from primary production to consumption, and climate change may have direct and indirect impacts on their occurrence. There are many pathways through which climate related factors may impact food safety including: changes in temperature and precipitation patterns, increased frequency and intensity of extreme weather events, ocean warming and acidification, and changes in the transport pathways of complex contaminants (***Tirado et al. 2010***).

Climate change may affect agriculture and food security by altering the spatial and temporal distribution of rainfall, and the availability of water, land, capital, biodiversity and terrestrial resources. It may heighten uncertainties throughout the food chain, from farm to fork and yield to trade dynamics, and ultimately impact on the global economy, food security and the ability to feed nine billion people by 2050. Modelling by IIASA (***Fischer et al. 2007***) shows that future socioeconomic development and climate change may impact on regional and global irrigation requirements and thus on agricultural water withdrawals. Net irrigation requirements may increase by 45% by 2080. Even with improvements in irrigation efficiency, gross water withdrawals may increase by 20%. Global irrigation requirements with climate change will increase by 20% above the reference base case scenario (without climate change). The simulation shows that the global impacts of climate change on irrigation water requirements could be as large as the projected increase in irrigation due to socioeconomic development (***Hanjra and Qureshi, 2010***).

Temperature increases and changes in rainfall patterns have an impact on the persistence and patterns of occurrence of bacteria, viruses, parasites and fungi and the patterns of their corresponding food borne diseases. Such changes also have an impact on microbial ecology and growth, plant and animal physiology and host susceptibility which may result in the emergence, redistribution and changes in the incidence and intensity of plant and animal diseases and pest infestations, all of which could impact food borne diseases and zoonoses (***FAO, 2008a***). In this context climate change and variability also pose a challenge to pest and diseases control measures such as Good Agriculture and Good Veterinary Practices with potential implications for the presence of chemical residues in the food chain.

Extreme weather events such as floods and droughts may lead to contamination of soil, agricultural lands, water and food and animal feed with pathogens, chemicals and other hazardous substances, originating from sewage, agriculture and industrial settings. Emergency situations after natural disasters are of special concern for water and food sanitation. Ocean warming, and climate change related acidification and changes in ocean salinity and precipitation also affect the biochemical properties of water, along with water microflora, fisheries distribution, fish metabolic rates, and persistence and patterns of occurrence of pathogenic vibrios, harmful algal blooms and chemical contaminants in fish and shellfish (***Tirado et al. 2010***).

The impacts of climate change on food production, prices and numbers at risk of hunger depend on a number of factors. These include regional climate change, biological effects of increasing atmospheric carbon dioxide, changes in floods, droughts and other extreme events, existing agricultural systems, adaptive capacity, changes in population, economic growth and technological innovation. A number of studies cited in the **IPCC (2007)** WGII report used the SRES family of scenarios of greenhouse gas emissions and socio-economic change (***Schmel, 2006***).

New conclusions reported by **IPCC (2007)** include that: (1) increases in frequency of extremes may lower crop yields beyond the impacts of average climate change, (2) impacts of climate change on irrigation water requirements may be large (as also are changes in irrigation water supply), (3) stabilization of CO_2 concentrations through reduced emissions reduces damage to crop production in the long term, despite loss of the physiological benefits of higher CO_2 concentrations, (4) the effects of lowers regional and global impacts, and (5) the magnitude of climate impacts will be small compared to that from different socio-economic development paths; sun-Saharan Africa is likely to surpass Asia as the most food-insecure region (***TRS, 2008***).

2.2.7 *Effects on Postharvest Quality of Fruit and Vegetable Crops*

Climate on Earth has changed many times during the existence of our planet, ranging from the ice ages to periods of warmth. During the last several decades increases in average air temperatures have been reported and associated effects on climate have been debated worldwide in a variety of forums. Due to its importance around the globe, agriculture was one of the first sectors to be studied in terms of potential impacts of climate change. Many alternatives have been proposed to growers aimed at minimizing losses in yield. However, few studies have addressed changes in postharvest quality of fruits and vegetable crops associated with these alterations. Nowadays, climate changes, their causes and consequences, gained importance in many other areas of interest for sustainable life on Earth. According to studies carried out by the IPCC, average air temperatures will increase between 1.4 and 5.8 ºC by the end of this century, based upon modeling techniques that incorporated data from ocean and atmospheric behavior. The possible impacts of this study, however, are uncertain since processes such as heat, carbon, and radiation exchange among different ecosystems are still under investigation. Less drastic estimates predict temperature increase rates of 0.088 ºC per decade for this century. Other investigators forecast for the near future that rising air temperature could induce more frequent occurrence of extreme drought, flooding or heat waves than in the past (***Moretti et al. 2010***).

Higher temperatures can increase the capacity of air to absorb water vapor and, consequently, generate a higher demand for water. Higher evapotranspiration indices could lower or deplete the water reservoir in soils, creating water stress in plants during dry seasons. For example, water stress is of great concern in fruit production, because trees are not irrigated in many production areas around the world. It is well documented that water stress not only reduces crop productivity but also tends to accelerate fruit ripening (***Henson, 2008***).

Exposure to elevated temperatures can cause morphological, anatomical, physiological, and, ultimately, biochemical changes in plant tissues and, as a consequence, can affect growth and development of different plant organs. These events can cause drastic reductions in commercial yield. However, by understanding plant tissues physiological responses to high temperatures, mechanisms of heat tolerances and possible strategies to improve yield, it is possible to predict reactions that will take place in the different steps of fruit and vegetable crops production, harvest and postharvest. Besides increase in temperature and its associated effects, climate changes are also a consequence of alterations in the composition of gaseous constituents in the atmosphere. Carbon dioxide (CO_2), also known as the most important greenhouse gas, and ozone (O_3) concentrations in the atmosphere are changing during the last decade and are affecting many aspects of fruit and vegetable crops production around the globe (***Lloyd and Farquhar, 2008***).

Carbon dioxide concentrations are increasing in the atmosphere during the last decades. The current atmospheric CO_2 concentration is higher than at any time in the past 420,000 years. Further increases due to anthropogenic activities have been predicted. Carbon dioxide concentrations are expected to be 100% higher in 2100 than the one observed at the pre-industrial era (***IPCC, 2007a***). Ozone concentration in the atmosphere is also increasing. Even low-levels of ozone in the vicinities of big cities can cause visible injuries to plant tissues as well as physiological alterations (***Felzer et al. 2007***).

It well documented that, climate changes can potentially cause postharvest quality alterations in fruit and vegetable crops. Although many researchers have addressed climate changes in the past and, in some cases, focused postharvest alterations, the information is not organized and available for postharvest physiologists and food scientists that are interested in better understanding how these changes will affect their area of expertise. **Moretti et al. (2010)** reviewed how changes in ambient temperature and levels of carbon dioxide and ozone can potentially impact the postharvest quality of fruit and vegetable crops.

After crops are harvested, respiration is the major process to be controlled. Postharvest physiologists and food scientists do not have many options to interfere with the respiratory process of harvested commodities, since they are largely dependent on the product specific characteristics. In order to minimize undesirable changes in quality parameters during the postharvest period, growers and entrepreneurs can adopt a series of techniques to extend the shelf-life of perishable plant products. Postharvest technology comprises different methods of harvesting, packaging, rapid cooling, storage under refrigeration as well as modified (MA) and controlled (CA) atmospheres and transportation under controlled conditions, among other important technologies. This set of strategies is of paramount importance to help growers all over the world to withstand the challenges that climate changes will impose throughout the next decades (***Moretti et al. 2010***).

Temperature increase and the effects of greenhouse gases are among the most important issues associated with climate change. Studies have shown that the production and quality of fresh fruit and vegetable crops can be directly and indirectly affected by high temperatures and exposure to elevated levels of carbon dioxide and ozone. ***Temperature*** increase affects photosynthesis directly, causing alterations in sugars, organic acids, and flavonoids contents, firmness and antioxidant activity. ***Carbon dioxide*** accumulation in the atmosphere has directly effects on postharvest quality causing tuber malformation, occurrence of common scab, and changes in reducing sugars contents on potatoes. High concentrations of atmospheric ***ozone*** can potentially cause reduction in the photosynthetic process, growth and biomass accumulation. Ozone-enriched atmospheres increased vitamin C content and decreased emissions of volatile esters on strawberries. Tomatoes exposed to ozone concentrations ranging from 0.005 to 1.0 μmol mol^{-1} had a transient increase in β-carotene, lutein and lycopene contents. It could be summarized the most important atmospheric factors, which affecting on postharvest fruit and vegetable crops as follows:

(1) *Effects of temperature*:

Understanding how climate changes will impact mankind in the decades to come is of paramount importance for our survival. Temperature, carbon dioxide and ozone directly and indirectly affect the production and quality of fruit and vegetable crops grown in different climates around the world. Temperature variation can directly affect crop photosynthesis, and a rise in global temperatures can be expected to have significant impact on postharvest quality by altering important quality parameters such as synthesis of sugars, organic acids, antioxidant compounds and firmness. Extensive work has been carried out for more than three decades focusing quality properties of fruit and vegetable crops exposed to high temperatures during growth and development.

- It is well known that, fruit and vegetable growth and development are influenced by different environmental factors.
- During their development, high temperatures can affect photosynthesis, respiration, aqueous relations and membrane stability as well as levels of plant hormones, primary and secondary metabolites.
- Seed germination can be reduced or even inhibited by high temperatures, depending on the species and stress level.
- Most of the temperature effects on plants are mediated by their effects on plant biochemistry.
- For plants that are subjected to water deficit, temperature is a physical facilitator for balancing sensible and latent heat exchange at the shoot, which is modulated by relative humidity and by wind. Most of the physiological processes go on normally in temperatures ranging from 0 ºC to 40 ºC.
- A general temperature effect in plants involves the ratio between photosynthesis and respiration.
- For a high yield, not only photosynthesis should be high but also the ratio photosynthesis/respiration should be much higher than one.
- At temperatures around 15 ºC, the above mentioned ratio is usually higher than ten, explaining why many plants tend to grow better in temperate regions than in tropical ones.
- Higher than normal temperatures affect the photosynthetic process through the modulation of enzyme activity as well as the electron transport chain (***Sage and Kubien, 2007***). Additionally, in an indirect manner, higher temperatures can affect the photosynthetic process increasing leaf temperatures and, thus, defining the magnitude of the leaf-to-air vapor pressure difference (D), a key factor influencing stomatal conductance (***Lloyd and Farquhar, 2008***).
- Photosynthetic activity is proportional to temperature variations. High temperatures can increase the rate of biochemical reactions catalyzed by different enzymes. However, above a certain temperature threshold, many enzymes lose their function, potentially changing plant tissue tolerance to heat stresses.
- Temperature is of paramount importance in the establishment of a harvest index. The higher the temperature during the growing season, the sooner the crop will mature.
- Flavor is affected by high temperatures. Apple fruits exposed to direct sunlight had a higher sugar content compared to those fruits grown on shaded sides. Grapes also had higher sugar content and lower levels of tartaric acid when grown under high temperatures.

- Fruit firmness is also affected by high temperature conditions during growth. ‘Fuerte’ avocados exposed to direct sunlight (35 ºC) were 2.5 times firmer than those positioned on the shaded side (20 ºC) of the tree. Changes in cell wall composition, cell number, and cell turgor properties were postulated as being associated with the observed phenomenon.
- Dry matter content is used as a harvest indicator for avocados due to its direct correlation with oil content, a key quality component.
- Thus, fruit and vegetable growers, packers and shippers must pay close attention to ambient temperatures during growth and development as well as maturity indices to assure harvest at the appropriate time.
- Mineral accumulation was also reported to be affected by high temperatures and/or direct sunlight.
- Antioxidants in fruit and vegetable crops can also be altered by exposure to high temperatures during the growing season. The investigators also observed that high temperature conditions significantly increased the levels of flavonoids and, consequently, antioxidant capacity.
- It was verified that higher temperatures tended to reduce vitamin content in fruit and vegetable crops.
- Exposure of fruit and vegetable crops to high temperatures can result in physiological disorders and other associated internal and external symptoms (**Table 2.8**).
- Exposure of tomato fruits to temperatures above 30 ºC suppresses many of the parameters of normal fruit ripening including color development, softening, respiration rate and ethylene production.
- It is also well known that exposure of fruit to temperature extremes approaching 40 ºC can induce metabolic disorders and facilitate fungal and bacterial invasion. Although symptoms of heat injury and disease incidence are easily observed at the end of storage, the incipient incidence of these disorders is often not recognized in time to effect corrective treatment.
- Practical effects of climate change have already been experienced in some parts of the globe (***Moretti et al. 2010***).

(2) *Effects of carbon dioxide exposure*:

The Earth’s atmosphere consists basically of nitrogen (78.1%) and oxygen (20.9%), with argon (0.93%) and carbon dioxide (0.031%) comprising next most abundant gases (***Lide, 2009***). Nitrogen and oxygen are not considered to play a significant role in global warming because both gases are virtually transparent to terrestrial radiation. Rising levels of carbon dioxide also contribute to global warming, by entrapping heat in the atmosphere. Prolonged exposure to CO_2 concentrations could induce higher incidences of tuber malformation and increased levels of sugars in potato and diminished protein and mineral contents, leading to loss of nutritional and sensory quality.

- The greenhouse effect is primarily a combination of the effects of water vapor, CO_2 and minute amounts of other gases (methane, nitrous oxide, and ozone) that absorb the radiation leaving the Earth's surface.
- The warming effect is explained by the fact that CO_2 and other gases absorb the Earth's infrared radiation, trapping heat. Since a significant part of all the energy emanated from Earth occurs in the form of infrared radiation, increased CO_2 concentrations mean that more energy will be retained in the atmosphere, contributing to global warming (***Lloyd and Farquhar, 2008***).
- Carbon dioxide concentrations in the atmosphere have increased approximately 35% from pre-industrial times to 2005 (***IPCC, 2007a***). Besides industrial activities, agriculture also contributes to the emission of greenhouse gases.
- Many papers published during the last decade have clearly associated global warming with the increase in carbon dioxide concentration in the atmosphere. Changes in CO_2 concentration in the atmosphere can alter plant tissues in terms of growth and physiological behavior.
- Many of these effects have been studied in detail for some vegetable crops. These studies concluded, in summary, that increased atmospheric CO_2 alters net photosynthesis, biomass production, sugars and organic acids contents, stomatal conductance, firmness, seed yield, light, water, and nutrient use efficiency and plant water potential (***Moretti et al. 2010***).

(3) *Effects of ozone exposure*:

Ozone in the troposphere is the result of a series of photochemical reactions involving carbon monoxide (CO), methane (CH_4) and other hydrocarbons in the presence of nitrogen species ($NO + NO_2$). It forms during periods of high temperature and solar irradiation, normally during summer seasons. It is also formed, naturally during other seasons, reaching the peak of natural production in the spring. However, higher concentrations of atmospheric ozone are found during summer due to increase in nitrogen species and emission of volatile organic compounds. Increased levels of ozone in the atmosphere can lead to detrimental effects on postharvest quality of fruit and vegetable crops. Elevated levels of ozone can induce visual injury and physiological disorders in different species, as well as significant changes in dry matter, reducing sugars, citric and malic acid, among other important quality parameters.

- Concentrations are at maximum values in the late afternoon and at minimum values in the early morning hours, notably in industrialized cities and vicinities. The opposite phenomenon occurs at high latitude sites. Another potential source for increased levels of ozone in a certain region is via the movement by local winds or downdrafts from the stratosphere.
- The effects of ozone on vegetation have been studied both under laboratory and field experiments. Stomatal conductance and ambient concentrations are the most important factors associated with ozone uptake by plants.

- Ozone enters plant tissues through the stomates, causing direct cellular damage, especially in the palisade cells. The damage is probably due to changes in membrane permeability and may or may not result in visible injury, reduced growth and, ultimately, reduced yield.
- Visible injury symptoms of exposure to low ozone concentrations include changes in pigmentation, also known as bronzing, leaf chlorosis, and premature senescence (***Felzer et al. 2007***).
- Since leafy vegetable crops are often grown in the vicinity of large metropolitan areas, it can be expected that increasing concentrations of ozone will result in increased yellowing of leaves. Leaf tissue stressed in this manner could affect the photosynthetic rate, production of biomass and, ultimately, postharvest quality in terms of overall appearance, color and flavor compounds (**Table 3**).
- Additionally, it is observed that ozone exposure causes reduction in photosynthesis and increased turnover of antioxidant systems.
- The review of the pertinent literature related to plant responses to ozone exposure reveals that there is considerable variation in species response. Greatest impacts in fruit and vegetable crops may occur from changes in carbon transport (***Moretti et al. 2010***).
- Underground storage organs (e.g., roots, tubers, bulbs) normally accumulate carbon in the form of starch and sugars, both of which are important quality parameters for both fresh and processed crops. If carbon transport to these structures is restricted, there is great potential to lower quality in such important crops as potatoes, sweet potatoes, carrots, onions and garlic.
- Exposure of other crops to elevated concentrations of atmospheric ozone can induce external and internal disorders, which can occur simultaneously or independently. These physiological disorders can lower the postharvest quality of fruit and vegetable crops destined for both fresh market and processing by causing such symptoms as yellowing (chlorosis) in leafy vegetables, alterations in starch and sugars contents of fruits and in underground organs.
- Decreased biomass production directly affects the size, appearance and other important visual quality parameters. Furthermore, impaired stomatal conductance due to ozone exposure can reduce root growth, affecting crops such as carrots, sweet potatoes and beet roots (***Felzer et al. 2007***).

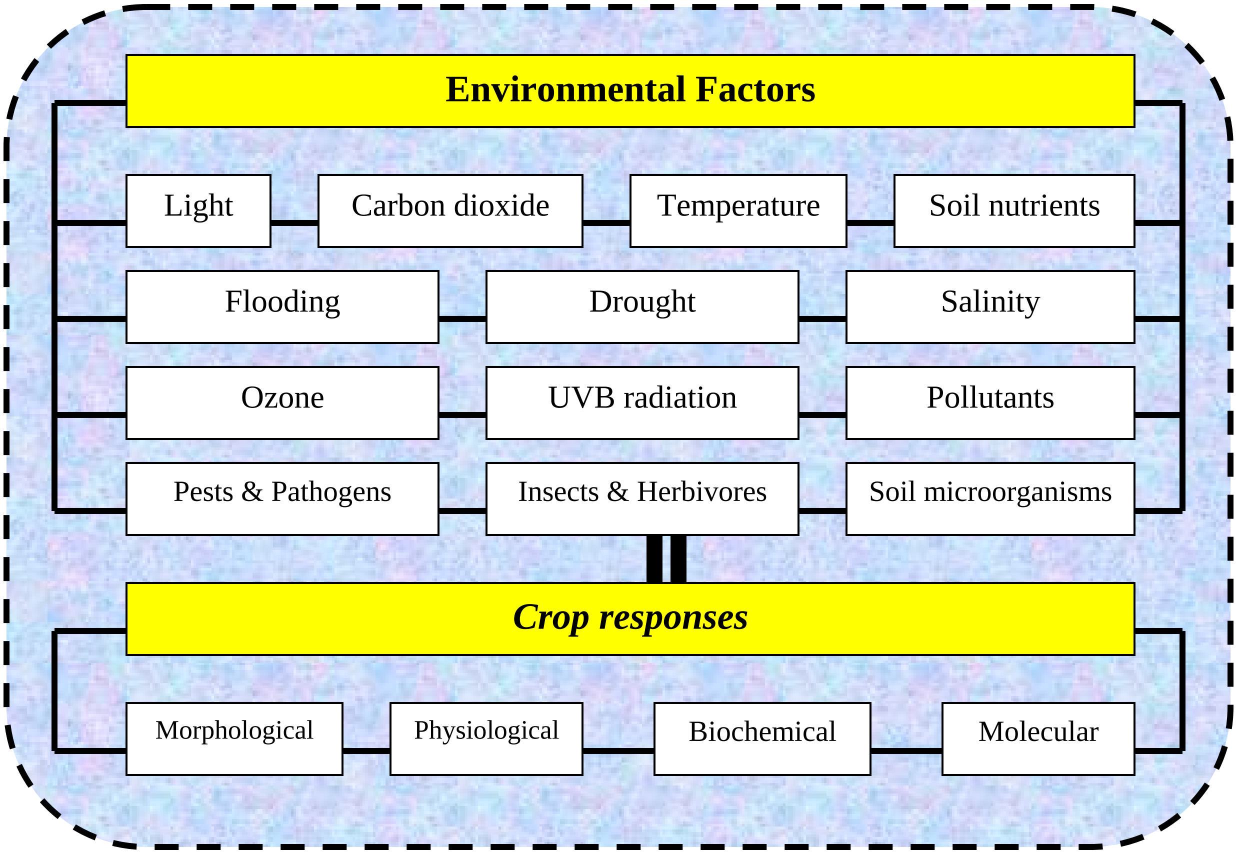


Figure 2.3: Crop responses to CO_2, temperature and other environmental factors (adapted from ***Qaderi and Reid, 2009***)

Table 2.8: Responses of some crop species to the stimulatory effects of elevated CO_2 at high temperature (adapted from ***Qaderi and Reid, 2009***)

Crop	Environment*	References
Strong response		
Bean	Controlled-environment chamber (CEC)	Cowling and Sage (1998)
Peanut	Greenhouse (GH)	Vu (2005)
Rice	Free-air CO_2 enrichment (SPAR)	Borjigidai et al. (2006)
Soybean	Growth chamber (GC)	Sionit et al. (1987)
Sweet potato	Greenhouse	Cen and Sage (2005)
Wheat	Open-top chamber	Hakala (1998)
Weak response		
Cotton	EGC- soil-plant-atmosphere-research unit	Reddy et al. (2005)
Cowpea	Growth chamber	Ahmed et al. (1993)
Bean	Sunlit - Controlled-environment chamber	Prasad et al. (2002)
Peanut	EGC- soil-plant-atmosphere-research unit	Prasad et al. (2005)
Rice	Greenhouse	Ziska et al. (1996)
Soybean	Sunlit Controlled-environment chamber	Thomas et al. (2003)
Wheat	Chamber - Greenhouse	Mitchell et al. (1993)

* C, chamber; OTC, open-top chamber; CEC, controlled-environment chamber; SPAR, soil-plant atmosphere-research unit; GC, growth chamber; FACE, free-air CO_2 enrichment; GH, greenhouse

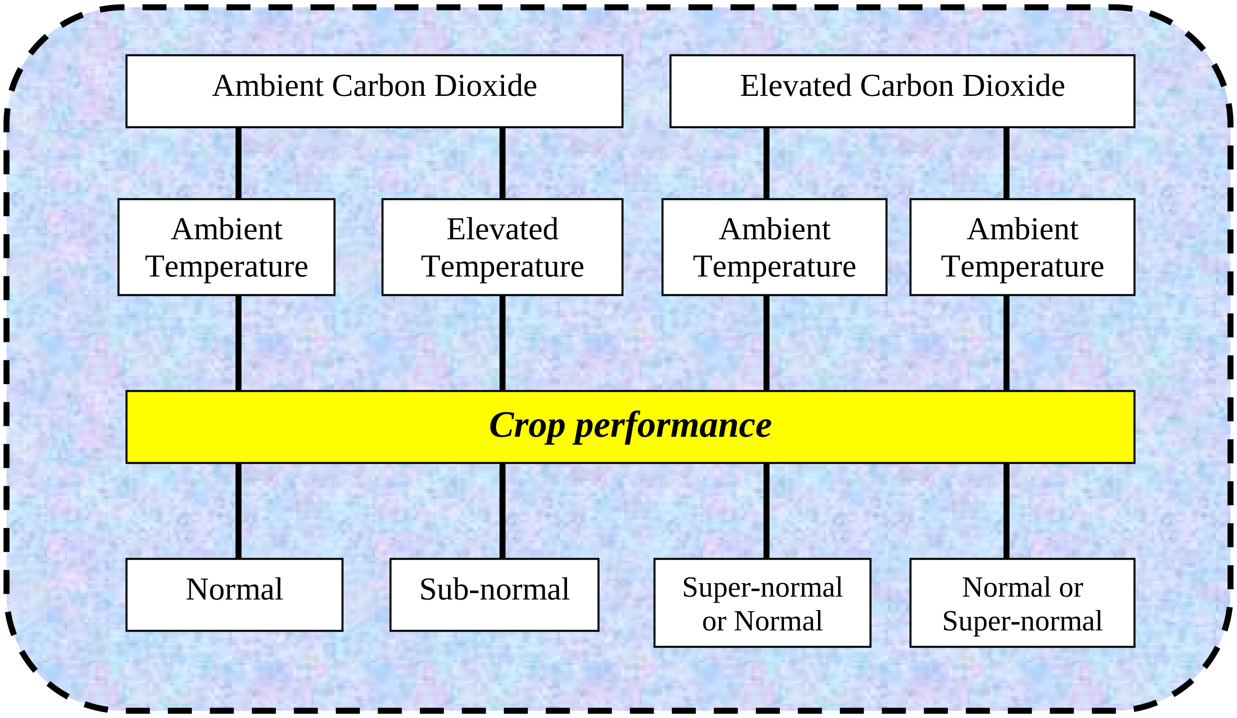


Figure 2.4: Crop responses to the combined effects of CO_2 and temperature (adapted from ***Qaderi and Reid, 2009***)

2.2.8 *Impacts Climate Changes on Pest and Disease Prevalence*

In a wonderful book about "Climate change and crop production" for **Reynolds (2010)** and in a chapter entitled "Scenarios of climate change within the context of agriculture" for **Jarvis et al.**, they analyzed the effects of climate changes on agriculture and its scenarios. They stated that, global climatic change is also likely to impact agriculture through shifts in patterns of pests and diseases (organisms that range from weeds, certain herbivorous insects, arthropods and nematodes to fungi, bacteria and viruses). Rising temperatures and variations in precipitation, humidity and other abiotic factors are affecting the diversity and responsiveness of agricultural pests and diseases across diverse geographic ranges (***Estay et al. 2009***). Of all the factors that influence the productivity of agricultural pests and diseases, temperature is cited as the most important to insect ecology, epidemiology and distribution, while humidity and rainfall patterns and temperature are what define the responsiveness of plant pathogens (***Hatfield et al. 2008***).

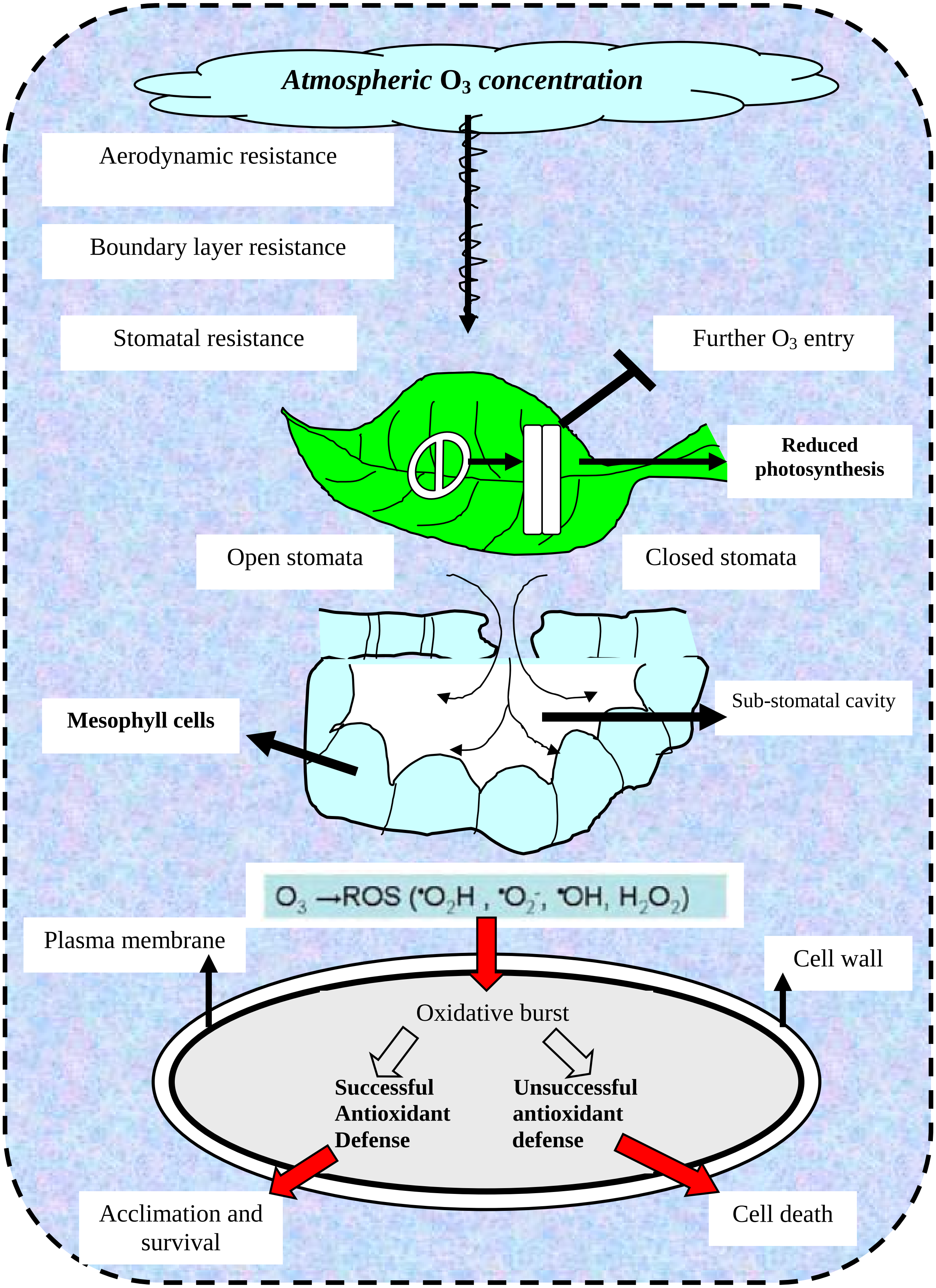

Atmospheric O3 concentration
Aerodynamic resistance
Boundary layer resistance
Stomatal resistance
Further O3 entry
Reduced photosynthesis
Open stomata
Closed stomata
Mesophyll cells
Sub-stomatal cavity
O3 →ROS (•O2H , •O2-, •OH, H2O2)
Plasma membrane
Cell wall
Oxidative burst
Successful Antioxidant Defense
Unsuccessful antioxidant defense
Acclimation and survival
Cell death

Figure 2.5: Simplified scheme of O_3 transfer, plant uptake and cell response (adapted from ***Vandermeiren et al. 2009***)

There are, however, few studies which quantify likely impacts on pest and disease prevalence due to the scarcity of system level studies that examine multi-trophic complexities between causal and ancillary agents (***Newton et al. 2008***). For example, where crops are enriched by augmented atmospheric CO_2 concentrations, pest/disease attacks are expected to negate optimization effects. Moreover, where positive impacts are highlighted (e.g. expanded range of cultivars, climatic fertilization enhancement), overriding negative consequences (in terms of biodiversity, yield, mitigation costs, etc.) are predicted to offset gains (***Diffenbaugh et al. 2008***). While predictions are more certain on which specific pathogens and pests will thrive under greater variability in climate, what is difficult to say with certainty is what effects they will have on similarly climate-stressed crops (***Thomson et al. 2009***). Thus, a shroud of doubt still lingers as to the forecasting of climate warming on agriculture–plague interactions. This is because, aside from climate change effects, developing new pest species and the spread of existing ones are caused by (***Cannon and Moran, 2008***):

- Natural expansion into unfilled ranges;
- Active dissemination on vehicles;
- Passive transport on traded plants and plant products; and
- Active flight (migrant species).

Numerous citations note the abundance and frequency of pests and diseases as likely to increase as local climates are adjusted outside their previously bounded norms (***FAO, 2008; Gregory et al. 2009***), especially in situations where crops are moved to previously unsuitable areas (***Thomson et al. 2009***). **FAO (2008)** cites **Cannon (2008)** who in a cursory report lists no less than 17 agricultural pests whose geographic coverage, species incidence and/or intensity will threaten to bring about impacts on agricultural production under climate change (***Jarvis et al. 2010***).

It is well established that, under climate change, characterized by increased temperatures and CO_2 levels, the fitness of plant herbivore pests is adjusting as their distributions and niches vary along with ambient conditions. In turn, their relationships with their natural enemies, phenologies (i.e. arrival and emergence times) and pressures from different pests and pathogens are noted in the scientific literature (***Garrett et al. 2006***). The physiological changes in plants growing under new extremes and farmers' adjusted management strategies will largely determine how these dynamics play out (i.e. it is difficult to say with certainty which groups of contaminants will increase or decrease and on which crops). Numerous studies are finding that herbivorous insect outbreaks are expected to increase in both frequency and intensity as global climate varies.

While the impacts of pests on yields and productivity are undoubtedly affected by a multitude of factors that are both biotic and abiotic, effective and proven biological controls in the form of pests' natural predators are not to be overlooked as a factor that impacts agricultural potential. **Thomson *et al.* (2009)** address climate change effects on herbivores and parasitoids of crops and cultivars and how disruptions in climate factors are adjusting fitness and competition for their natural enemies. Direct and indirect aspects of phenological modifications in plants are affecting the fecundity and abundance of herbivores, disadvantaging their natural predators. Increases in ambient CO_2 and temperature, and adjustments of humidity and precipitation rates are adjusting the availability of food resources for many pests, to their advantage and disadvantage, depending on the species involved.

In reference to biotic changes, climate alterations may affect microclimates around plants resulting in increased risk of infection from wetness and root diameter (***Garrett et al. 2006***). Moreover, elevated levels of CO_2 can bring about positive effects both indirectly (reduced expression of induced resistance in plants). Climate modifications affecting diseases are also linked to food safety concerns. For example the propensity for the spread of food borne pathogens from the greater temporal range of diseases during planting seasons has been noted (***Gregory et al. 2009***).

It is well known that, preventing plant diseases has always been a major concern in agriculture and a cornerstone of breeding efforts to obtain higher yields. Although recent decades have seen major changes in ecosystems as a result of agriculture intensification, producing enough food for the growing population remains a major global challenge. A range of forces influence food systems and food security, but the global food supply needs to double by 2050, with the current world population of about 6.7 billion being projected to reach 9.5 billion by the mid-21st century (***Borlaug, 2009***).

Human-induced climate change and increasing climate variability, resulting from the increase in the atmospheric concentration of greenhouse gases (GHGs), are recognized unequivocally. The fourth report of the Intergovernmental Panel on Climate Change (IPCC) established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) summarizes this evidence (***IPPC, 2007***). The most obvious effect is on the global mean temperature, which is expected to rise between 0.9 and 3.5°C by the year 2100. Cold days and nights and frost have become less frequent over most land areas, whereas hot days and nights are becoming more frequent. The melting of the ice caps and snow cover, resulting in rising sea levels, the variation in the frequency, timing and intensity of precipitation, leading to unusual floods mainly in coastal areas, and mid-term or severe drought in other regions, are well documented (***IPCC, 2007***).

Since plant diseases reduce crop performance and are considerably affected by environmental parameters, it is likely that major changes in eco-climatic conditions will lead to changes in plant disease frequency and severity, threatening the quantity and quality of agricultural products. Several reviews highlight the growing concern for the potential impact of climate change on plant diseases (e.g.,

Gregory et al. 2009). New cropping practices, globalization and international trade have a rapid effect on the plant disease spectrum. Recent climatic changes undeniably observed worldwide give a new dimension to the evolution and distribution of plant pathogen populations resulting from crop intensification and long-term climate evolution. This makes it even more likely that plant disease evolution and its control will require increased emphasis in the future under changing climate scenarios.

Although the epidemiology of many plant patho-systems (Robinson, 1976) is now better understood, it is difficult to separate climate change effects on the parameters affecting plant disease from normal seasonal variations. The effects of global climate change on plant diseases are subtle, progressive and difficult to document because of the scarcity of long-term data sets (***Jeger and Pautasso, 2008***), resulting in uncertainty about possible future scenarios. Conclusions about a specific crop disease are often deduced from limited studies on one or a few specific physical variables (e.g. temperature, CO_2 concentration and drought) conducted under controlled conditions, whereas multiple interactions occur in the context of climate change. Studying and understanding the drivers of change are essential if actions are to be implemented that prevent or reduce their impact (***Legrève and Duveiller, 2010***).

2.2.9 *Effects on animal production and sustainability of livestock systems*

It is well known that the key conclusions of Working Group I of the Intergovernmental Panel on Climate Change (IPCC), the Fourth Assessment Report (AR4) (***IPCC, 2007***) were:

a) Warming of the climatic system is unequivocal;

b) Anthropogenic warming will probably continue for centuries due to the timescales associated with climate processes and feedbacks;

c) The surface air warming in the 21st century by best estimate will range from 1.1 to 2.9 °C for a "low scenario" and of 2.4 to 6.4 °C for a "high scenario".

Moreover, the IPCC report estimates a confidence level > 90% that there will be more frequent warm spells, heat waves and heavy rainfall and a confidence level > 66% that there will be an increase in drought, tropical cyclones and extreme high tides. The magnitude of the events will vary depending on the geographic zones of the World. The AR4 has been subjected to scientific criticism. It has been said that the report understates or overstates the dangers of climate change, and overstates the faults due to anthropogenic greenhouse gas concentrations. Nevertheless, the recognized scientists contributing to the IPCC report and the results of our analysis of the evolution of temperature–humidity index (THI) in the Mediterranean area in the last five decades of 20th century (data unpublished) convince us to follow the theory of global warming. The effects of global warming will not be adverse everywhere in the world (***Nardone et al. 2010***).

Despite the importance of livestock to poor people and the magnitude of the changes that are likely to befall livestock systems, the intersection of climate change and livestock in developing countries is a relatively neglected research area. Little is known about the interactions of climate and increasing climate variability with other drivers of change in livestock systems and in broader development trends. In many places in the tropics and subtropics, livestock systems are changing rapidly, and the spatial heterogeneity of household response to change may be very large. While opportunities may exist for some households to take advantage of more conducive rangeland and cropping conditions, for example, the changes projected will pose serious problems for many other households. Although, the effects of global warming will not be adverse everywhere, a relevant increase of drought is expected across the world affecting forage and crop production. Hot environment impairs production (growth, meat and milk yield and quality, egg yield, weight, and quality) and reproductive performance, metabolic and health status, and immune response. The process of desertification will reduce the carrying capacity of rangelands and the buffering ability of agro-pastoral and pastoral systems. Other systems, such as mixed systems and industrial or landless livestock systems, could encounter several risk factors mainly due to the variability of grain availability and cost, and low adaptability of animal genotypes. Regarding livestock systems, it will be strategic to optimize productivity of crops and forage (mainly improving water and soil management), and to improve the ability of animals to cope with environmental stress by management and selection. To guide the evolution of livestock production systems under the increase of temperature and extreme events, better information is needed regarding biophysical and social vulnerability, and this must be integrated with agriculture and livestock components.

A huge increase in the demand of animal production is expected in the next decades. Food and water security will be one of the other priorities for humankind in the 21st century. Over the same period the World will experience a change in the global climate that will cause shifts in local climate that will impact on local and global agriculture. **Thornton et al. (2007)** forecast a slight increase in crop productivity at mid to high latitude for an increased local mean temperature of 1–3 °C. Also in these areas, frosts, heat waves or heavy rainfall can cancel the advantages of the increase in temperature. A lower increase of temperature, around 1–2 °C, however, could worsen crop and cereal production at lower latitudes. The areas affected most will be in the boreal hemisphere, in particular North America, Northern Europe, Northern Asia and, at a lower latitude, the Mediterranean basin and West-Central Asia (***Easterling et al. 2007***).

Some countries in these areas have a very high farm animal density and animal production comes mostly from industrialized livestock systems, which rear highly selected pigs, poultry and dairy cows. The indirect effects of global warming such as soil infertility, water scarcity, grain yield and quality and diffusion of pathogens may impair animal production in these systems more than the direct effects. Indeed, in these systems the animals can cope better with the direct effects of high temperature, i.e. heat stress, with the help of diet, techniques of cooling or farm management. On the other hand, the employment of techniques to adapt air temperature of barns to the thermo-neutrality of the animals causes higher energy consumption and therefore, worsens global warming and increases general costs of animal production. Moreover, industrialized systems produce more manure than can be used as fertilizer on nearby cropland resulting in soil accumulation of phosphorous, nitrogen and other pollutants (***Thorne, 2007***).

Livestock systems in developing countries are changing rapidly in response to a variety of drivers. Globally, human population is expected to increase from around 6.5 billion today to 9.2 billion by 2050. More than 1 billion of this increase will occur in Africa. Rapid urbanization is expected to continue in developing countries, and the global demand for livestock products will continue to increase significantly in the coming decades. The potential impact of these drivers of change on livestock systems and the resource-poor people who depend on them for their livelihoods is considerable. These impacts will be influenced by both supply-side shifts in natural resource use as well as marketed demand changes. Given the complexity of livestock (and in most cases crop–livestock) systems in developing countries, a mix of technological, policy and institutional innovations will be required. On the technology side, improvements will be linked to a combination of feed and nutrition, genetics and breeding, health and environmental management options, with different combinations appropriate to different systems (***Thornton et al. 2009***).

Significant changes in physical and biological systems have already occurred on all continents and in most oceans, and most of these changes are in the direction expected with warming temperature (***Rosenzweig et al. 2008***). For the future, there is considerable uncertainty, but recent ‘‘best estimates” of temperature increases from the IPCC in the Fourth Assessment Report (AR4) are in the range 1.8–4 ºC in 2090–2099 relative to 1980–1999, depending on the scenario of future greenhouse-gas emissions that is used to drive the climate models (***IPCC, 2007***). The impacts of temperature increases at even the lower end of this range will be far-reaching. At the lower end of the range of temperature rise (1–3 ºC), global food production might actually increase but above this range would probably decrease. However, broad trends will be overshadowed by local differences, as the impacts of climate change are likely to be highly spatially variable. Climate change will alter the regional distribution of hungry people, with particularly large negative effects in sub-Saharan Africa. Smallholder and subsistence farmers, pastoralists and artisanal fisherfolk will suffer complex, localized impacts of climate change, due both to constrained adaptive capacity in many places and to the additional impacts of other climate related processes such as snow-pack decrease, particularly in the Indo-Gangetic Plain, and sea-level rise (***IPCC, 2007***). Furthermore, changes in the frequency and severity of extreme climate events will have significant consequences for food production and food security; it is not only projected mean climate change that will have an impact. Increasing frequencies of heat stress, drought and flooding events are estimated to be likely, even though they cannot be modeled in any satisfactory way with current levels of understanding of climate systems, but these will have adverse effects on crop and livestock productivity over and above the impacts due to changes in mean variables alone (***IPCC, 2007***; ***Thornton et al. 2009***).

The challenges for development are already considerable, and there is now general concern that climate change and increasing climate variability will compound these. However, there is only limited knowledge about the interactions of climate with other drivers of change in agricultural systems and on broader development trends. Such work is increasingly important for evaluating how farming systems may evolve in the future. It should be understood the likely impacts of climate change on vulnerable people through its effects in and on other sectors. These include impacts on water resources and other ecosystems goods and services, and human health and nutrition, for example. Enhanced understanding is needed of the likely impacts of climate change on the vulnerability of the resource-poor, so that resilience to current climate variability as well as to the risks associated with longer-term climate change can be gauged, and appropriate actions set in place to increase or restore resilience where this is threatened (***Thornton et al. 2009***).

It is expected that the livestock systems based on grazing and the mixed farming systems will be more affected by global warming than an industrialized system. This will be due to the negative effect of lower rainfall and more droughts on crops and on pasture growth and of the direct effects of high temperature and solar radiation on animals. These systems exist mainly in developing countries where the human demand for animal products is increasing due to the continuous growth in the population and per capita consumption. A loss of 25% of animal production by global warming (***Seguin, 2008***) is foreseen in these countries. A worse scenario is foreseen for Africa and some zones of Asia where extensive or pasture based systems remain the norm. In any case at a World level, animal production has to increase in the next decades to satisfy the growing need. It is estimated that by 2050, global meat consumption will be twice that of today. How can we make animal production equal animal consumption in the next decades? The challenge will be how to better balance either the increase in the number of stock or the productivity per head, at the same time improving the sustainability of the livestock sector. This is an important task as today the billion land animals which are reared and slaughtered, either directly or indirectly contribute to total human induced greenhouse gas by 18% and total CO_2 emission by 9%. The efficiency of water utilization will be another primary mission necessary to achieve sustainability of animal agriculture in expectation of increasing water scarcity and worsening quality. To save water means to grow plants and to rear animals in systems demanding less water. The question is where and under what conditions in the World will it be convenient to produce animal products? Animal production requires high volumes of water per unit of product. An example is beef that demands about 23 tons of water per kg of product. Animal agriculture will face hard challenges in many fields in the 21st century. Decision makers, research institutions and extension services have to support livestock activities to cope at best with the loss of production, worsening of animal products, enlargement of land desertification and the worsening of animal health under the effects of the climate change we expect in the next decades (***Nardone et al. 2010***).

It could be analyzed some relevant effects of global warming on livestock production and on the forecast of the evolution of major livestock systems. It is not to foresee the global evolution of animal production and livestock systems under the effects of climate change owing to the enormous number of components under either direct or indirect climatic effects that shape livestock systems. It could be also in briefly reviewing some elements of the complex relationship between livestock and climate change in developing countries. Classification of livestock systems in developing countries and the impacts of climate change on livestock are be considered. Livestock have obvious impacts on water resources and biodiversity, as well as these things being affected by climate change and having impacts on livestock.

Anthropogenic climate change has recently become a well established fact and the resulting impact on the environment is already being observed. The greenhouse effect is a key mechanism of temperature regulation. Without it, the average temperature of the earth's surface would not be 15ºC but -6ºC. The earth returns energy received from the sun back to space by reflection of light and by emission of heat. A part of the heat flow is absorbed by so-called *greenhouse gases*, trapping it in the atmosphere. The principal greenhouse gases involved in this process include carbon dioxide (CO_2), methane (CH_4) nitrous oxide (N_2O) and chlorofluorocarbons. Since the beginning of the industrial period anthropogenic emissions have led to an increase in concentrations of these gases in the atmosphere, resulting in global warming. The average temperature of the earth's surface has risen by 0.6 degrees Celsius since the late 1800s.

Recent projections suggest that average temperature could increase by another 1.4 to 5.8 °C by 2100 (***UNFCCC, 2005***). Even under the most optimistic scenario, the increase in average temperatures will be larger than any century-long trend in the last 10 000 years of the present-day interglacial period. Ice-core based climate records allow comparison of the current situation with that of preceding interglacial periods. Global warming is expected to result in changes in weather patterns, including an increase in global precipitation and changes in the severity or frequency of extreme events such as severe storms, floods and droughts. Climate change is likely to have a significant impact on the environment. In general, the faster the changes, the greater will be the risk of damage exceeding our ability to cope with the consequences. Mean sea level is expected to rise by 9–88 cm by 2100, causing flooding of low lying areas and other damage. Climatic zones could shift poleward and uphill, disrupting forests, deserts, rangelands and other unmanaged ecosystems. As a result, many ecosystems will decline or become fragmented and individual species could become extinct (***IPCC, 2001a***).

The levels and impacts of these changes will vary considerably by region. Societies will face new risks and pressures. Food security is unlikely to be threatened at the global level, but some regions are likely to suffer yield declines of major crops and some may experience food shortages and hunger. Water resources will be affected as precipitation and evaporation patterns change around the world. Physical infrastructure will be damaged, particularly by the rise in sea-level and extreme weather events. Economic activities, human settlements, and human health will experience many direct and indirect effects. The poor and disadvantaged, and more generally the less advanced countries are the most vulnerable to the negative consequences of climate change because of their weak capacity to develop coping mechanisms **(*Steinfeld et al. 2006*)**.

Livestock globally play a considerable role in climate change, in terms of their contribution to greenhouse-gas emissions. Livestock activities have significant impact on virtually all aspects of the environment, including air and climate change, land and soil, water and biodiversity. The impact may be direct, through grazing for example, or indirect, such as the expansion of soybean production for feed replacing forests in South America. Livestock's impact on the environment is already huge, and it is growing and rapidly changing. Global demand for meat, milk and eggs is fast increasing, driven by rising incomes, growing populations and urbanization. As an economic activity, livestock production is technically extremely diverse. In countries or areas where there is no strong demand for food products of animal origin, subsistence and low in put production prevails, mainly for subsistence rather than for commercial purposes. This contrasts with commercial, high-input production in areas serving a growing or established high demand. Such diverse production systems make extremely diverse claims on resources. The diversity of production systems and interactions makes the analysis of the livestock–environment interface complex and sometimes controversial. The livestock sector affects a vast range of natural resources, and must be carefully managed given the increasing scarcity of these resources and the opportunities that they represent for other sectors and activities. While intensive livestock production is booming in large emerging countries, there are still vast areas where extensive livestock production and its associated livelihoods persist. Both intensive and extensive production requires attention and intervention so that the livestock sector can have fewer negative and more positive impacts on national and global public goods **(*Steinfeld et al. 2006*)**.

Global agriculture will face many challenges over the coming decades and climate change will complicate these. A warming of more than 2.5°C could reduce global food supplies and contribute to higher food prices. The impact on crop yields and productivity will vary considerably. Some agricultural regions, especially in the tropics and subtropics, will be threatened by climate change, while others, mainly in temperate or higher latitudes, may benefit. The livestock sector will also be affected. Livestock products would become costlier if agricultural disruption leads to higher grain prices. In general, intensively managed livestock systems will be easier to adapt to climate change than will crop systems. Pastoral systems may not adapt so readily. Pastoral communities tend to adopt new methods and technologies more slowly, and livestock depend on the productivity and quality of rangelands, some of which may be adversely affected by climate change. In addition, extensive livestock systems are more susceptible to changes in the severity and distribution of livestock diseases and parasites, which may result from global warming **(*Steinfeld et al. 2006*)**.

As the human origin of the greenhouse effect became clear, and the gas emitting factors were identified, international mechanisms were created to help understand and address the issue. The United Nations Framework Convention on Climate Change (UNFCCC) started a process of international negotiations in 1992 to specifically address the greenhouse effect. Its objective is to stabilize greenhouse gas concentrations in the atmosphere within an ecologically and economically acceptable timeframe. It also encourages research and monitoring of other possible environmental impacts, and of atmospheric chemistry. The direct warming impact is highest for carbon dioxide simply because its concentration and the emitted quantities are much higher than that of the other gases. Methane is the second most important greenhouse gas. Once emitted, methane remains in the atmosphere for approximately 9–15 years. Methane is about 21 times more effective in trapping heat in the atmosphere than carbon dioxide over a 100- year period. Atmospheric concentrations of CH_4 have increased by about 150 percent since pre-industrial times, although the rate of increase has been declining recently. It is emitted from a variety of natural and human-influenced sources. The latter include landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment and certain industrial process (***US-EPA, 2005***). The IPCC has estimated that slightly more than half of the current CH_4 flux to the atmosphere is anthropogenic (***IPCC, 2001b***). Total global anthropogenic CH_4 is estimated to be 320 million tonnes CH_4/yr, i.e. 240 million tonnes of carbon per year. This total is comparable to the total from natural sources. Nitrous oxide, a third greenhouse gas with important direct warming potential, is present in the atmosphere in extremely small amounts. However, it is 296 times more effective than CO_2 in trapping heat and has a very long atmospheric lifetime (114 years) **(*Steinfeld et al. 2006*)**.

Livestock activities emit considerable amounts of these three gases. Direct emissions from livestock come from the respiratory process of all animals in the form of carbon dioxide. Ruminants, and to a minor extent also monogastrics, emit methane as part of their digestive process, which involves microbial fermentation of fibrous feeds. Animal manure also emits gases such as CH_4, nitrous oxides,

NH_3 and CO_2, depending on the way they are produced (solid, liquid) and managed (collection, storage, spreading). Livestock also affect the carbon balance of land used for pasture or feed crops, and thus indirectly contribute to releasing large amounts of carbon into the atmosphere. The same happens when forest is cleared for pastures. In addition, greenhouse gases are emitted from fossil fuel used in the production process, from feed production to processing and marketing of livestock products. Some of the indirect effects are difficult to estimate, as land use related emissions vary widely, depending on biophysical factors as soil, vegetation and climate as well as on human practices **(*Steinfeld et al. 2006*)**.

Classification of livestock systems in the developing world

It could be used the systems classification of **Seré and Steinfeld (1996)**, whose methods were built on the concept of the agro-ecological zone. There are two parts to the classification. The agro-climatic part is based on the length of growing period (LGP), defined as the period in days during the year when the rainfed available soil moisture supply is greater than half the potential evapotranspiration (PET). It includes the period required to evapotranspire up to 100 mm of available moisture stored in the soil profile. Excluded are any time intervals with daily mean temperatures of less than 5 ºC. Three categories are defined:

1. Arid/semi-arid, with a LGP of less than or equal to 180 days;
2. Humid/sub-humid, with a LGP greater than 180 days;
3. Tropical highlands/temperate. Temperate regions are defined as those with one month or more with monthly mean temperature, corrected to sea level, below 5 ºC. Tropical highlands are defined as those areas with a daily mean temperature, during the growing period, of between 5 and 20 ºC.

The second part of the classification distinguishes between solely livestock systems and mixed farming systems. Solely livestock systems are those in which more than 90% of dry matter fed to animals comes from rangelands, pastures, annual forages and purchased feeds and less than 10% of the total value of production comes from non-livestock farming activities. Mixed farming systems are livestock systems in which more than 10% of the dry matter fed to animals comes from crop by-products, stubble or more than 10 percent of the total value of production comes from non-livestock farming activities. The solely livestock systems are split into two:

- ❖ Grassland-based systems, in which more than 10% of the dry matter fed to animals is farm produced and in which annual average stocking rates are less than 10 temperate livestock units per hectare of agricultural land.
- ❖ Landless livestock production systems, in which less than 10% of the dry matter fed to animals is produced on the farm and in which annual average stocking rates are above 10 temperate livestock units per hectare of agricultural land. The landless systems are further split into two categories:

landless monogastric systems, in which the value of production of the pig/poultry enterprises is higher than that of the ruminant enterprises; and landless ruminant systems, in which the value of production of the ruminant enterprises is higher than that of the pig/poultry enterprises (***Thornton et al. 2009***).

The classification system of **Seré and Steinfeld (1996)** thus has eleven system types: livestock only, rangeland-based (LG), which may be arid/semiarid (LGA), humid/sub-humid (LGH), or tropical highland/temperate (LGT); landless monogastric-based (LLM), and landless ruminant-based (LLR); mixed, rainfed systems (MR) by the three agro-ecological zones, and mixed, irrigated systems (MI), also by the three agro-ecological zones. The systems are tabulated in **Figure 2.6.** Clearly, these systems may be affected by climate change in different ways. Impacts on the arid/semiarid rangelands (LGA) of Latin America or sub-Saharan Africa, for example, could be expected to be associated more with effects on pasture (as the major feed in these systems) and water availability, compared with impacts on the tropical-highland mixed, rainfed systems (MRT) of sub-Saharan Africa or South Asia, where the primary effects may be more on crop residues (as a key feeding resource), for example. The following section presents an overview of the impacts of climate change on livestock in relation to these different systems (***Thornton et al. 2009***).

Climate change's impacts on livestock

The effects of climate change on the health of farm animals have not been studied in depth. However, it can be assumed that as in the case of humans, climate change, in particular global warming, is likely to greatly affect the health of farm animals, both directly and indirectly. Direct effects include temperature-related illness and death, and the morbidity of animals during extreme weather events. Indirect impacts follow more intricate pathways and include those deriving from the attempt of animals to adapt to thermal environment or from the influence of climate on microbial populations, distribution of vector-borne diseases, host resistance to infectious agents, feed and water shortages, or food-borne diseases. It could be organised impacts of climate change on livestock under seven headings: feeds, quantity and quality; heat stress; water; livestock diseases and disease vectors; biodiversity; systems and livelihoods; and indirect impacts.

It could be concluded that increasing of temperatures cause severe damage to the physiology, the metabolism and to the healthiness of animals. Modification of existing regimes of precipitation and the increase of aridity will have repercussions on the availability of feedstuff for animals. The increased difficulty in livestock production in the world will correspond to the increasing needs in animal products.

There is still a great deal that is not well understood concerning the interactions of climate and increasing climate variability with other drivers of change in livestock systems and in broader development trends. Multiple and competing pressures are likely on tropical and subtropical livestock systems in the future, to produce food, to feed livestock, and to produce energy crops, for example (**Table 2.9 and 2.10**).

Table 2.9: Livestock systems classification (adapted from ***Seré and Steinfeld, 1996***)

Generic	Specific	System
LG (livestock only)	LGA	Livestock only systems, arid–semiarid (LGP < 180 days)
	LGH	Livestock only systems, humid–subhumid (LGPP180 days)
	LGT	Livestock only systems, highland/temperate [a]
MR (mixed rainfed)	MRA	Mixed rainfed crop/livestock systems, arid–semiarid (LGP < 180 days)
	MRH	Mixed rainfed crop/livestock systems, humid–subhumid (LGPP180 days)
	MRT	Mixed rainfed crop/livestock systems, highland/temperate [a]
MI (mixed irrigated)	MIA	Mixed irrigated crop/livestock systems, arid–semiarid (LGP < 180 days)
	MIH	Mixed irrigated crop/livestock systems, humid–subhumid (LGPP180 days)
	MIT	Mixed irrigated crop/livestock systems, highland/temperate [a]
LL (landless)	LLM	Landless monogastric systems
	LLR	Landless ruminant systems

[a] Temperate regions: areas with one or more months with monthly mean temperature, corrected to sea level, of less than 5 ºC. Tropical highlands: areas with a daily mean temperature, during the growing period, of 5 – 20 ºC.

Table 2.10: Some of the knowledge gaps of climate change impacts on livestock-based systems and livelihoods in the tropics and subtropics (adapted from ***Thornton et al. 2009***)

Area	Gap
Feeds: quantity and quality	Rangelands (LG): primary productivity impacts, species distribution and change due to CO_2 and other competitive factors, estimation of carrying capacities
	Mixed systems (MR, MI): localized impacts on primary productivity, harvest indexes and stover production
Heat stress	What is the extent of the problem, in a development context?
Water	Surface and groundwater supply, and impacts on livestock (particularly LG systems)
	Effective ways to increase livestock water productivity
Diseases and disease vectors	How may the prevalence and intensity of key epizootic livestock diseases change in the future?
	How may climate change affect diseases as systems intensify (particularly MR, MI, LL systems)?
Biodiversity	Ecological biodiversity': what will happen to numbers of species as systems change?
	Animal breed biodiversity: can the animal genetic resources that might be useful in the future be specified?
Livestock systems	Localized impacts on livelihoods
	How will systems evolve in future?
	Magnitude and effects of systems changes on ecosystems goods and services
Indirect impacts	How do human health impacts of climate change intertwine with livelihood systems and vulnerability?

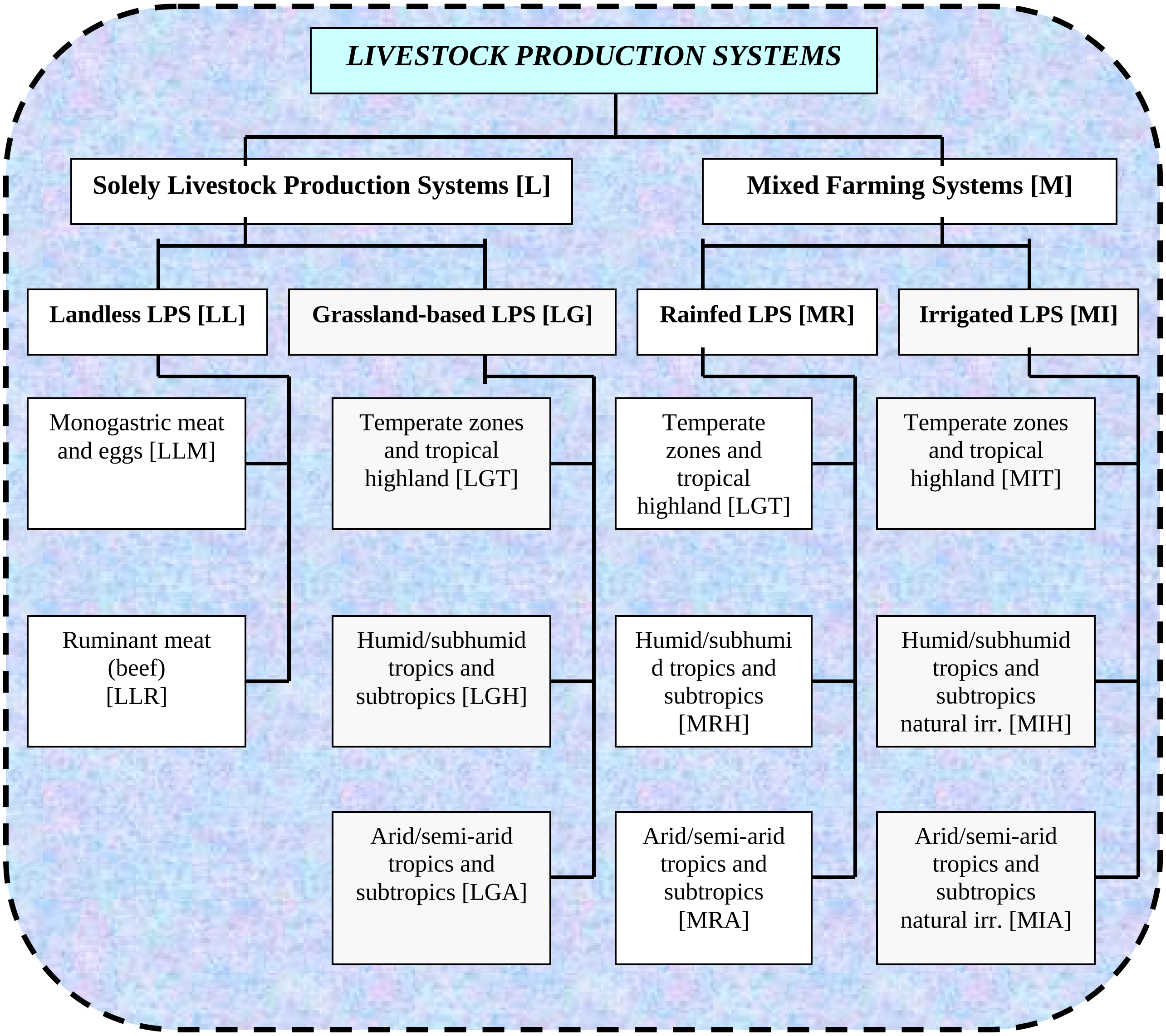


Figure 2.6: Classification of livestock production systems (adapted ***Seré and Steinfeld, 1996***)

The answers of the livestock systems to these requisites will be diverse. The grazing and mixed rain-fed systems, which count on the availability of pastures and farm crops, will be the most damaged by climate change. The positive trend both in the number of heads and in productivity that we observed in recent decades could slowdown or even become negative, if an effort is not made to adapt. Livestock and livestock systems are substantial users of natural resources and globally they contribute significantly to global warming, while at the same time they make contributions of critical importance to the livelihoods of at least a billion poor people in rural households, almost all of whom are in developing countries. Damage could be considerable, since grazing and mixed rain-fed systems raise almost 70% of all ruminants in the world. Worldwide they produce almost 2/3 of the milk and meat from ruminants. Moreover more that 50% of this production is raised in developing countries where the need of animal products will increase more.

At the moment it seems difficult to evaluate whether or not the areas lost to desertification caused by climate change, will be compensated by the zones favored by the change in climate. The need for twice the amount of animal products in the next 4 decades should be satisfied essentially by the irrigated and industrial systems. How could this happen? An increase in heads and also better indices of productivity in these systems are predictable. Therefore, we will have more pigs and poultry, point that is already being confirmed by the growing trend in pork and poultry production. Furthermore, because of the difficulties of grazing and rain-fed systems, milk and beef production will shift to industrialized systems, even though this increase in industrialized production will be more moderate than poultry and pork.

Scientific research can help the livestock sector in the battle against climate change. All animal scientists must collaborate closely with colleagues of other disciplines, first with agronomists then, physicists, meteorologists, engineers, economists, etc. The effort in selecting animals that up to now has been primarily oriented toward productive traits, from now on, must be oriented toward robustness, and above all adaptability to heat stress. In this way molecular biology could allow to directly achieve genotypes with the necessary phenotypic characteristics.

Research must continue developing new techniques of cooling systems such as thermo-isolation, concentrating more than in the past on techniques requiring low energy expenditure. New indices that are more complete than THI to evaluate the climatic effects on each animal species must be developed and weather forecast reports must also be developed with these indices, to inform the farmers in advance.

Above all to beat the climate change or in any case not to let the climate beat livestock systems, researchers must be very aware of technologies of water conservation. In the future we can profit, more than in the past, from the years of experience of the people living in arid zones by applying our scientific knowledge to useful traditional practices (***Nardone et al. 2010***).

2.2.10 *Climate change and biodiversity*

Biodiversity is a term used to encompass the variety of life on Earth. It refers to the variety of all life forms: the different plants, animals and micro-organisms, their genes, and the communities and ecosystems of which they are part. Biodiversity is usually recognized at three levels: genetic diversity, species diversity and ecosystem diversity. It is most often used with reference to the variety and number of species and subspecies (e.g. the diversity of birds is approximately 10 000 species), and it also applies to genetic variation within species, differences between populations, and variation at higher levels of organization such as the community or ecosystem, or even variation within a biome (***Steffen et al. 2009***).

The Intergovernmental Panel on Climate Change considered biodiversity to be the sector most at risk from the effects of rapid climate change (***Smith et al. 2009***). Globally, significant biodiversity loss has already occurred from land clearing, the effects of invasive species, and large changes in natural disturbance regimes (***Xingli et al. 2010***). Climate change and land-use change are both key drivers of biodiversity change. Interactions between these drivers are complex and currently not well understood (***Duraiappah et al. 2005; Fischlin et al. 2007***), and may have a greater overall impact on biodiversity change than either of these drivers operating in isolation (***Root and Schneider, 2006; Brook, 2008***). In spite of this, most biodiversity studies assess the impacts of climate change (e.g. ***Malcolm et al. 2006***) or land-use change and associated habitat fragmentation (e.g. ***Fazey et al. 2005***) in isolation. Furthermore, only a small number of biodiversity studies include the effects of land-use change in contrast to the large number of studies of climate change. Calls have been made for studies that integrate both drivers (e.g. ***Fischlin et al. 2007; Brook, 2008; Thuiller et al. 2008***) however only a few such studies have been undertaken to date (e.g. ***Bomhard et al. 2005; Jetz et al. 2007; de Chazal and Rounsevell, 2009***).

Climate change poses major new challenges to biodiversity conservation. As atmospheric CO_2 increases over the next century, it is expected to become the first or second greatest driver of global biodiversity loss (***Thomas et al. 2004***). Global average temperatures have increased 0.2°C per decade since the 1970s, and global average precipitation increased 2% in the last 100 years (***IPCC, 2007a***). Moreover, climate changes are spatially heterogeneous. Some locations, such as the Arctic, experience much larger changes than global means, while others are exposed to secondary effects like sea level rise (***IPCC, 2007a***). Climate change may have already resulted in several recent species extinctions (***Pounds et al. 2006***). Many species ranges have moved poleward and upward in elevation in the last century (***Root et al. 2003***) and will almost certainly continue to do so. Local communities are disaggregating and shifting toward more warm adapted species (***Parmesan, 2005***). Phenological changes in populations, such as earlier breeding or peak in biomass, are decoupling species interactions (***Walther et al. 2002***). These changes raise concerns about the effectiveness of existing biodiversity protection strategies (**Table 2.11**; ***Scott et al. 2002; Heller and Zavaleta, 2009***).

Biodiversity conservation relies predominately on fixed systems of protected areas, and the mandated goals of many conservation agencies and institutions are to protect particular species assemblages and ecosystems within these systems (***Scott et al. 2002***). With the magnitude of climate change expected in the current century, many vegetation types and individual species are expected to lose representation in protected areas (***Lemieux and Scott, 2005***).

Table 2.11: Examples of microbiological agents that could be affected by climate change and variability and their mode of transmission to humans (adapted from ***Tirado et al. 2010***)

Bacteria	***Host***	***Mode of transmission to humans***
Salmonella	Poultry and pigs	Faecal/oral
Campylobacter	Poultry	Faecal/oral
Vibrio spp.	Shellfish, Fish	Faecal/oral
E. coli O157	Cattle and other ruminants	Faecal/oral
Anthrax Clostridium	Livestock and wild birds	Ingestion of spores through environmental routes, water, soil and feeds. Associated with outbreaks of after droughts
Yersinia	Birds and rodents with regional differences in the species of animal infected. Pigs are a major reservoir	Handling pigs at slaughter is a risk to humans
Listeria monocytogenes	Livestock	In the northern hemisphere, listeriosis has a distinct seasonal occurrence in livestock probably associated with feeding of silage
Leptospira	All farm animal species	Leptospirae shed in urine to contaminate pasture, drinking water and feed
Virus	Host	Mode of transmission to humans
Rift Valley fever Virus	Multiple species of livestock and wildlife	Blood or organs of infected animals (handling of animal Tissue), unpasteurized or uncooked milk of infected animals, mosquito, hematophagous flies
Nipah virus	Bats and pigs	Directly from bats to humans through food in the consumption of date palm sap (***Luby et al. 2006***). Infected pigs present a serious risk to farmers and
Hendra virus	Bats, and horse	abattoir workers
Hantavirus	Rodents	Secretions from infected horses
		Aerosol route from rodents. Outbreaks from activities
Hepatitis E virus	Wild and domestic animals	Such as clearing rodent infested areas and hunting.
		Faecal-oral. pig manure is a possible source through
Encephalitis tick borne virus	Sheep, goats	contamination of irrigation water and shellfish
Parasites	Host	Unpasteurized milk
		Mode of transmission to humans
Tapeworm *Cysticercus bovis*	Cattle	Faecal-oral
Liver fluke		
Protozoan parasites	Sheep, cattle	Eggs are excreted in faeces
Toxoplasma Gondii		
	Cats, pigs, sheep	Cat faeces are a major source of infection. Handling and
Cyptosporidium		consuming raw meat from infected sheep and pigs
	Cattle, sheep	Faecal-oral transmission. Waterborne. (Oo)cysts are highly infectious and with high loadings, livestock
Giardia		faeces pose a risk to animal handlers
	Cattle, cats, dogs	Faecal-oral transmission. Waterborne

Reserves at high latitudes and high elevations, on low-elevation islands and the coast, and those with abrupt land use boundaries are particularly vulnerable. Landscapes outside of protected areas are hostile to the survival of many species due to human infrastructure and associated stressors, such as invasive species, hunting, cars, and environmental toxins. Such fragmentation directly limits species migration and gene flow. Projected rates of climate change are also faster than they were in the past – so rapid that in situ genetic adaptation of most populations to new climate conditions is not likely (***Jump and Penuelas, 2005***), nor is migration likely to be fast enough for many species. Moreover, even if major global action reduced emissions significantly within the next years or capped them at year 2000 levels, the thermal inertia of the oceans will continue to drive climate change for decades and will require adaptive responses (***Wigley, 2005***). A recent update of atmospheric CO_2 growth rate, which has more than doubled since the 1990s as global economic activity increases and becomes more carbon-intensive, makes clear that significant global emissions reductions are a distant goal at best (***Canadell et al. 2007; Heller and Zavaleta, 2009***).

Heller and Zavaleta (2009) recorded 524 recommendations from 113 papers, published in 57 different source journals and three books. Recommendations ranged from calls for specific types of modeling (e.g. inexact-fuzzy multi-objective programming to broad shifts in governance structures (**Table 2.12**).

Climate change, land-use change and biodiversity encompass a range of definitions and respective characterizations, which in turn generates a range of different relationships between and as a consequence of these two drivers. Climate change usually refers to change over time in variables such as temperature, precipitation and wind with increases in temperature being a particular focus (***Parry et al. 2007***). Climate change is typically considered in terms of having a negative impact on biodiversity, although a range of other responses are also reported, albeit less considered (e.g. ***Thomas et al. 2006***). Land-use (the purpose for and manner in which biophysical attributes of the earth's surface and immediate subsurface are manipulated) as distinct from land cover (the biophysical state of the earth's surface and immediate subsurface) change (***Turner II et al. 1995***) represents a wide range of conversions including to and from forest, grassland, cultivated land, and urban land. The most commonly considered is a conversion of (native) forest or grassland habitat into cultivated or urban land. This land-use conversion has been the most important conversion in terms of land areas in the recent past and potentially will continue to be so in the future (***Alcamo et al. 2006***). It also represents the key conversion leading to the greatest loss of biodiversity (***Lambin et al. 2003; Duraiappah et al. 2005***). Other important aspects of land-use change include habitat fragmentation (***Fahrig, 2003***), and differences in management intensity within the same land-use.

Table 2.12: List of recommendations for climate change adaptation strategies for biodiversity management assembled from 112 scholarly articles. 524 records were condensed into 113 recommendation categories and are ranked by frequency of times cited in different articles (only the first 5 ranking and for more details see ***Heller and Zavaleta, 2009***)

Rank	*Recommendation*	*No. articles*	*References*
1	Increase connectivity (design corridors, remove barriers for dispersal, locate reserves close to each other, reforestation	**24**	Beatley (1991), Chambers et al. (2005), Collingham and Huntley (2000), Da Fonseca et al. (2005), de Dios et al. (2007), Dixon et al. (1999), Eeley et al. (1999), Franklin et al. (1992), Guo (2000), Halpin (1997), Hulme (2005), Lovejoy (2005), Millar et al. (2007), Morecroft et al. (2002), Noss (2001), Opdam and Wascher (2004), Rogers and McCarty (2000), Schwartz et al. (2001), Scott et al. (2002), Shafer (1999), Welch (2005), Wilby and Perry (2006) and Williams (2000)
2	Integrate climate change into planning exercises (reserve, pest outbreaks, harvest schedules, grazing limits, incentive programs	**19**	Araujo et al. (2004), Chambers et al. (2005), Christensen et al. (2004), Dale and Rauscher (1994), Donald and Evans (2006), Dyer (1994), Erasmus et al. (2002), Hulme (2005), Le Houerou (1999), McCarty (2001), Millar and Brubaker (2006), Peters and Darling (1985), Rounsevell et al. (2006), Scott and Lemieux (2005), Scott et al. (2002), Soto (2001), Staple and Wall (1999), Suffling and Scott (2002) and Welch (2005)
3	Mitigate other threats, i.e. invasive species, fragmentation, pollution	**17**	Bush (1999), Chambers et al. (2005), Chornesky et al. (2005), Da Fonseca et al. (2005), de Dios et al. (2007), Dixon et al. (1999), Halpin (1997), Hulme (2005), McCarty (2001), Noss (2001), Opdam and Wascher (2004), Peters and Darling (1985), Rogers and McCarty (2000), Shafer (1999), Soto (2001), Welch (2005) and Williams (2000)
4	Study response of species to climate change physiological, behavioral, demographic	**15**	Alongi (2002), Chambers et al. (2005), Crozier and Zabel (2006), Dyer (1994), Erasmus et al. (2002), Fukami and Wardle (2005), Gillson and Willis (2004), Honnay et al. (2002), Hulme (2005), Kappelle et al. (1999), McCarty (2001), Mulholland et al. (1997), Noss (2001), Peters and Darling (1985) and Swetnam et al. (1999)
	Practice intensive management to secure populations	**15**	Bartlein et al. (1997), Buckland et al. (2001), Chambers et al. (2005), Chornesky et al. (2005), Crozier and Zabel (2006), Dixon et al. (1999), Dyer (1994), Franklin et al. (1992), Hulme (2005), Morecroft et al. (2002), Peters and Darling (1985), Soto (2001), Thomas et al. (1999), Williams (2000) and Williams et al. (2005)
	Translocate species	**15**	Bartlein et al. (1997), Beatley (1991), Chambers et al. (2005), de Dios et al. (2007), Halpin (1997), Harris et al. (2006), Honnay et al. (2002), Hulme (2005), Millar et al. (2007), Morecroft et al. (2002), Pearson and Dawson (2005), Peters and Darling (1985), Rogers and McCarty (2000), Schwartz et al. (2001), Shafer (1999) and Williams et al. (2005)
5	Increase number of reserves	**13**	Burton et al. (1992), Dixon et al. (1999), Hannah et al. (2007), Hughes et al. (2003), Le Houerou (1999), Lovejoy (2005), Peters and Darling (1985), Pyke and Fischer (2005), Scott and Lemieux (2005) (2007), van Rensburg et al. (2004), Wilby and Perry (2006) and Williams et al. (2005)

In the context of climate change and land-use change, biodiversity is typically associated with species, most often referring to native or endemic species richness or species diversity (including species number and relative abundance). However, it is also used to represent a single species through to selected groups of species. Species responses to the various characterizations of climate change and land-use change vary considerably, depending on which species are considered, the way each species respectively responds to each driver, whether there are any interactions between drivers and between species and the spatial and temporal scale considered. Species may respond positively, negatively or exhibit no change in response to each driver. In the case of no interactions between drivers, a response to both drivers represents the sum of the individual responses. In the case of interactions between the drivers, the collective response variously represents more than the sum of the individual responses (exacerbation) or less than the sum (amelioration) (***de Chazal and Rounsevell, 2009***).

Sala et al. (2005) suggests that when taking three drivers into account (climate change, land-use change and nitrogen deposition), vascular plant species number and relative abundance may decrease by 12–16% by 2050 relative to species present in 1970. Land-use change accounts for between 23 and 36% of the change for biomes where climate change is the most important driver (cool conifer forests, savannas, and tundra) through to between 82 and 93% for biomes where habitat conversion to cultivated land or urban is the most important driver (warm mixed forests, temperate deciduous forests and tropical forests). Even with no assumed interactions between the drivers, biodiversity assessments based on climate change alone under this circumstance would lead to a significant under-estimation of biodiversity loss.

2.2.11 *Climate Changes and Land Use*

Land use describes use of the land surface by humans. Normally, use of land is defined in an economic context, so we think of land as it is used for agricultural, residential, commercial, and other uses. However, strictly speaking, we can seldom really see the use of the land, except on the very closest inspection, so we consider also *land cover*—the visible features of the Earth’s surface—included in the vegetative cover, natural and as modified by humans, its structures, transportation and communications, and so on (**Figure 2.7**). As a practical matter, it must be considered land use and land cover together, while also recognizing the distinction between the two.

Modern society depends on accurate land use data for both scientific and administrative purposes. They form an essential component of local and regional economic planning to ensure that various activities are positioned on the landscape in a rational manner. For example, accurate knowledge of land use patterns permits planning to avoid placing residential housing adjacent to heavy industry or in floodplains. Accurate land use information can ensure that residential neighborhoods are logically placed with respect to commercial centers and access to transportation services. In another context, land use is an important component of climatic and hydrologic modeling to estimate the runoff of rainfall from varied surfaces into stream systems. And accurate land use data are important for transportation planning, so traffic engineers can estimate the flow of vehicles from one region to another and design highways with appropriate capacities. Land use patterns also reflect the character of a society's intimate interaction with its physical environment. Although land use patterns within our own society seem self-evident and natural, other societies often organize themselves in contrasting patterns. This fact becomes obvious when it is possible to observe different economic and social systems occupying similar environments (***Campbell and Wynne, 2011)***.

Figure 2.7: Land use and land cover. *Land use* refers to the principal economic enterprises that characterize an area of land: agriculture, manufacturing, commerce, and residential. *Land cover* indicates the physical features that occupy the surface of the Earth, such as water, forest, and urban structures (adapted from ***Campbell and Wynne, 2011***)

Urban land use and land cover (LULC) datasets are very important sources for many applications, such as socioeconomic studies, urban management and planning, and urban environmental evaluation. The increasing population and economic growth have resulted in rapid urban expansion in the past decades. Therefore, timely and accurate mapping of urban LULC is often required. Although many approaches for remote sensing image classification have been developed, urban LULC classification is still a challenge because of the complex urban landscape and limitations in remote sensing data. Conventional survey and mapping methods do not provide the necessary information in a timely and cost-effective manner. Remotely sensed data, with their advantages in spectral, spatial, and temporal resolution, have demonstrated their power in providing information about the physical characteristics of urban areas, including size, shape, and rates of change, and have been used widely for mapping and monitoring of urban biophysical features. Geographic information system (GIS) technology provides a flexible environment for entering, analyzing, and displaying digital data from various sources that are necessary for urban feature identification, change detection, and database development. The integration of remote sensing and GIS technologies has been applied widely and has been recognized as an effective tool in urban-related research (***Weng, 2002***). Because of the confusion of spectral signatures in some land cover types, such as between impervious surface and soil and between low-density residential area and forest, ancillary data have become an important source for improving urban LULC classification accuracy. However, in urban areas, the separation of different densities of residential areas, the distinction between residential areas and forest or grass, and the separation of commercial/industrial areas from residential areas are important. Census data, such as those on housing density distribution, are closely related to urban LULC patterns. This chapter explores, based on a case study of Indianapolis, Indiana, the use of housing information in different stages in the image classification procedure in order to identify a suitable method for improvement of urban LULC classification performance (***Weng, 2010***).

Climate change and land-use change are both key drivers of biodiversity change. Interactions between these drivers are complex and currently not well understood, and may have a greater overall impact on biodiversity change than either of these drivers operating in isolation. In spite of this, most biodiversity studies assess the impacts of climate change or land-use change and associated habitat fragmentation in isolation. Furthermore, only a small number of biodiversity studies include the effects of land-use change in contrast to the large number of studies of climate change. Calls have been made for studies that integrate both drivers however only a few such studies have been undertaken to date (***de Chazal et al. 2009***).

An implication of the lack of integrated analysis is that studies of biodiversity change that examine the effect of either climate change or land-use change in isolation are likely to either over- or under-estimate the potential effects. Interactions between climate and land-use change may also lead to surprising outcomes. The individual and combined effects of climate change and land-use change on biodiversity are also determined by how these drivers as well as biodiversity are defined with different definitions resulting in a range of effects and interactions. In this paper we explore these issues in detail, highlighting the complexities that are associated with multi-driver analyses (***de Chazal et al. 2009***).

A much broader range of impacts of land-use/cover change on ecosystem goods and services were further identified. Of primary concern are impacts on biotic diversity worldwide, soil degradation, and the ability of biological systems to support human needs. Land-use/cover changes also determine, in part, the vulnerability of places and people to climatic, economic, or sociopolitical perturbations. When aggregated globally, land-use/cover changes significantly affect central aspects of Earth System functioning. All impacts are not negative though as many forms of land-use/cover changes are associated with continuing increases in food and fiber production, in resource-use efficiency, and in wealth and well-being.

Understanding and predicting the impact of surface processes on climate required long-term historical reconstructions – up to the last 300 years – and projections into the future of land-cover changes at regional to global scales. Quantifying the contribution of terrestrial ecosystems to global carbon pools and flux required accurate mapping of land cover and measurements of landcover conversions worldwide. Fine resolution, spatially explicit data on landscape fragmentation were required to understand the impact of land-use/cover changes on biodiversity. Predicting how land-use changes affect land degradation, the feedback on livelihood strategies from land degradation, and the vulnerability of places and people in the face of land-use/cover changes requires a good understanding of the dynamic human-environment interactions associated with land-use change (***Kasperson et al. 2005***).

Sustainable land use refers to the use of land resources to produce goods and services in such a way that, over the long term, the natural resource base is not damaged, and that future human needs can be met. The time horizon of the concept covers several generations. Over the last few decades, numerous researchers have improved measurement of land-cover change, the understanding of the causes of land-use change, and predictive models of land-use/cover change, in part under the auspices of the Land-Use and Land-Cover Change (LUCC) project of the International Geosphere-Biosphere Programme (IGBP) and International Human Dimensions Programme on Global Environmental Change (IHDP) (***Lambin et al. 2006***). Their work, part of an international effort that has helped to propagate the emergence of "land-change science," has taken on the task of demonstrating the role of land change in its own right within the Earth System. An "integrated land science" has emerged, uniting environmental, human, and remote sensing/GIS sciences to solve various questions about land-use and land-cover changes and the impacts of these changes on humankind and the environment. This science has demonstrated both the pivotal role of land change in the Earth System and its complexities that transcend such simplifications as unidirectional and permanent land-cover change caused by immediate population or consumption changes, replacing them by a representation of a much more complex process of land-use/cover change. The new Global Land Project (***Ojima, 2005***) is developing further land-change science based on the foundations generated by LUCC and by other projects on terrestrial ecosystems (***Lambin et al. 2006***).

Since time immemorial, humankind has changed landscapes in attempts to improve the amount, quality, and security of natural resources critical to its well being, such as food, freshwater, fiber, and medicinal products. Through the increased use of innovation, human populations have, slowly at first, and at increasingly rapid pace later on, increased its ability to derive resources from the environment, and expand its territory. Several authors have identified three different phases – the control of fire, domestication of biota, and fossil-fuel use – as being pivotal in enabling increased appropriation of natural resources (***Turner II and McCandless, 2004***).

Agriculture has been the greatest force of land transformation on this planet. Nearly a third of the Earth's land surface is currently being used for growing crops or grazing cattle (***FAO, 2004***). Much of this agricultural land has been created at the expense of natural forests, grasslands, and wetlands that provide valuable habitats for species and valuable services for humankind. It is estimated that roughly half of the original forests (ca. 8 000 years ago) have been lost (***Billington et al. 1996***). The pace of agricultural land transformation has been particularly rapid in the last 300 years. Much of the large-scale cultivation in 1700 was concentrated in the Old World, specifically in Europe, the Indo – Gangetic Plains, eastern China, and Africa. Roughly 2–3% of the global land surface was cultivated at that time. Since then, the rate of cropland expansion increased with scale, regional-scale trends are alarming. It is estimated that the United States of America paved over roughly 2.9 million ha of agricultural land between 1982 and 1997, and that ~30% of the increase in developed land during 1982–1997 occurred on prime farmland. China lost nearly 1 million ha of its cultivated land to expansion of infrastructure (both urban and rural) between 1988 and 1995. Some rough estimates indicate that 1 to 3 million ha of cropland may be taken out of production every year in developing countries to meet the land demand for housing, industry, infrastructure, and recreation (***Ramankutty et al. 2006***).

Before the 19th century, land in Sub-Saharan Africa was used largely for hunting, gathering, herding, and shifting cultivation. Some settled agriculture existed in Africa long before the imposition of colonial rule in the late nineteenth century, but in the pre-colonial period, demographic and economic needs allowed for land cleared for cultivation to be left fallow for long periods or abandoned as cultivators moved on and cleared new land. Estimates of cropland areas before ~1900 are variable, in part because of the lack of data and in part because "croplands" were part of a shifting cultivation rotation, where the distinctions between cropped areas and fallows are unclear. Shifting cultivation included annual clearing of 0.5–3.0 ha of forest per family creating a mosaic of cropped fields intermingled with fields 2–3 years old, fallows, and stands of secondary and mature forest. Clearing of previously cultivated areas (old fallows of 10–50 years) was generally preferred over clearing old-growth forests. Before ~1900, land use had probably been in a "quasi-equilibrium" for thousands of years. Changes included both increases and decreases as a result of wars, epidemics, famines, and slave trade (both intra-African and trans-Atlantic). In fact, populations are thought to have declined somewhat during the 19th century. Between 1850 and 1900 European colonization introduced changes; but with a few exceptions, the most rapid and dramatic changes occurred after 1930. The area under export crops expanded significantly because colonial governments needed the revenues they provided to recover from worldwide depression of the 1930s. In addition, by the 1930s, the railroads and most of the other major transport routes were in place in colonial Africa, and it became feasible to begin development of areas that had hitherto been inaccessible. This combination of demographic pressure and economic incentive has continued to the present. Cropland area in Sub-Saharan Africa is estimated to have been 119 million ha in 1961 and 163 million ha in 2000 (***FAO 2004***), an increase of 37% in 40 years. The rate of forest clearing for long-term shifting cultivation has been even greater than the rate of clearing for permanent croplands in recent decades (***Houghton and Hackler, 2006***).

Land use patterns change over time in response to economic, social, and environmental forces. The practical significance of such changes is obvious. For planners and administrators, they reveal the areas that require the greatest attention if communities are to develop in a harmonious and orderly manner. From a conceptual perspective, study of land-use changes permits identification of long-term trends in time and space and the formation of policy in anticipation of the problems that accompany changes in land use. Land use and land cover change is very simple in concept: Two maps representing the same region, prepared to depict land use patterns at different dates, are compared, point by point, to summarize differences between the two dates (**Figure 2.8**). In practice, compiling land use and land cover change requires mastery of several practical procedures that often reveal previously hidden difficulties. **First**, the two maps must use the same classification system, or at least two classification systems that are compatible. Compatible classifications mean that the classes can be clearly matched to one another without omission or ambiguity. For example, if one map represents forested land as a single category, "forest," and a second uses three classes— "coniferous," "deciduous"—and "mixed coniferous/deciduous," then the two maps are compatible in the sense that the three categories of the second maps can be combined into a single forested class that is logically compatible with the "forested" class on the first map. As long as the classes are matched at that level of generalization, one can be confident that the comparisons would reveal changes in the extent of forested land. However, if the second map employs classes such as "densely forested," "partially forested," and "sparsely forested," we could not reasonably match these classes to the "forested class" on this first map—the two sets of classes are not logically compatible (***Campbell and Wynne, 2011)***.

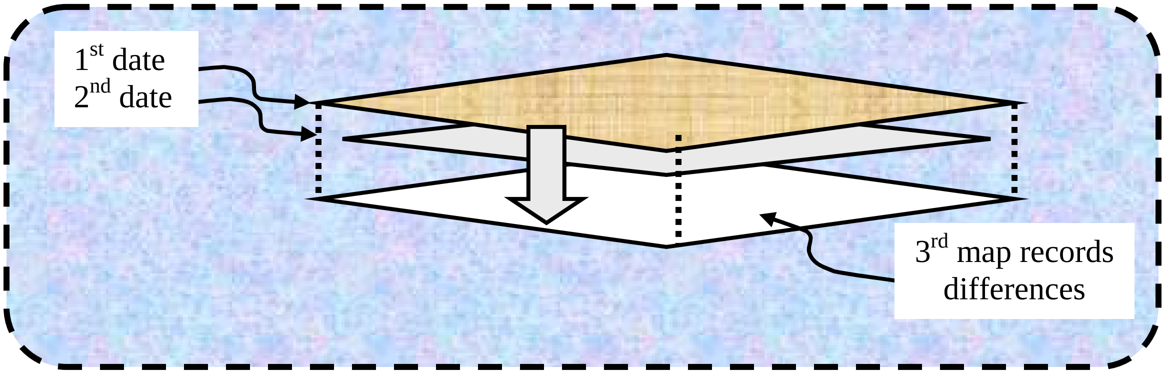


Figure 2.8: Schematic representation of compilation of land use change using sequential aerial imagery (adapted from ***Campbell and Wynne, 2011***)

The meanings conveyed by these classes, as represented on the two maps, are not equivalent, so they cannot be compared to determine whether the differences represent true change or simply differences in the way the maps were prepared. **Second**, the two maps must be compatible with respect to scale, geometry, and level of detail. Can we match one point on one map with the corresponding point on the second and be sure that both points refer to the same place on the Earth's surface? If not, we cannot conduct a change analysis using the two maps because we cannot be sure that differences in the two maps reflect genuine differences in land use and not simply differences in the projection, scale, or geometric properties of the two maps. These two basic conditions must be satisfied before change data can be complied using any two maps or images: compatibility of the information portrayed and geometric compatibility. Often, land use maps are prepared to meet the very specific objectives of the sponsoring organization. Therefore, it may be very difficult to reuse that map in a land use change study many years later. Objectives may have changed, or the level of detail, the classification system, and so forth, reflect the needs of a previous era. It is for this reason that it is common in land use change studies for maps to be prepared at the time of the study, using consistent materials, methods, and procedures, even if earlier studies already exist and are available (***Campbell and Wynne, 2011)***. It could be studied the land use and its relationship with global climate changes by the following topics:

(1) ***Recent Changes in Agricultural Areas***

Historically, humans have increased agricultural output mainly by bringing more land into production. The greatest concentration of farmland is found in Eastern Europe, with more than half of its land area under crops (***Ramankutty et al. 2002***). In the United Kingdom, about 70% of its area is classified as agricultural land (cropland, grassland/rough grazing), with agriculture and areas set aside for conservation or recreation intimately intertwined. Despite claims to the contrary, the amount of suitable land remaining for crops is very limited in most developing countries where most of the growing food demand originates. Where there is a large surplus of cultivable land, land is often under rain forest, permanent pastures, or in ecologically marginal areas (***Ramankutty et al. 2006***).

(2) ***Recent Changes in Pastoral Areas***

Natural vegetation covers have given way not only to cropland but also to pasture, defined as land used permanently for herbaceous forage crops, either cultivated or growing wild (**FAO, 2004**). The distinction between pasture and natural savannas or steppes is not always clear. In many parts of the world, such landscapes are “multifunctional”, making it difficult to classify them for inventories. Therefore, the LUCC-MA assessment did not deal with grazing land changes. Nevertheless, broad patterns can probably be derived from the FAO statistics, which show that most pastures are located in Africa (26% of the global total of ~35 million ha) and Asia (25%), and only a small portion is located in North America (8%) and Europe (2%) (**FAO, 2004**). Latin America and the Caribbean have 18% of the world’s pastures, while the FSU nations have 10%, and Oceania has 12%. During the last decade, pastures increased considerably in Asia and the FSU (6.8% and 10%, respectively), whereas the largest decreases were seen in Europe and Oceania. Data suggest that pasture land has apparently decreased in eastern Africa; however, as eastern Africa recorded a large increase in head of cattle over this period (872 000 additional head of cattle per year between 1992 and 1999, according to ***FAO, 2004***), it is likely that many pastoral areas in this part of Africa are classified as natural vegetation (**Figure 2.9**; ***Ramankutty et al. 2006***).

(3) ***Recent Changes in Urbanization***

In 2000, towns and cities housed more than 2.9 billion people, nearly half of the world population. Urban populations have been growing more rapidly than rural populations worldwide over the last two decades, particularly in developing countries. According to the UN Population Division (***United Nations Population Division, 2002***), the number of mega-cities, defined here as cities with more than 10 million inhabitants, has increased from one in 1950 (New York) to 17 in 2000, the majority of which are in developing countries. Urban form and function have also changed rapidly. Built-up or impervious areas are roughly estimated to occupy between 2% to 3% of the Earth’s land surface. This relatively small area reflects high urban population densities: for example, in 1997, the 7 million inhabitants of Hong Kong lived on as little as 120 km^2 of built-up land. However, urbanization affects land in rural areas through the ecological footprint of cities. This footprint includes, but is not restricted to, the consumption of prime agricultural land in peri-urban areas for residential, infrastructure, and amenity uses, which blurs the distinction between cities and countryside, especially in western developed countries. Urban inhabitants within the Baltic Sea drainage, for example, depend on forest, agriculture, wetland, lake, and marine systems that constitute an area about 1 000 times larger than that of the urban area proper (***Folke et al. 1997***).

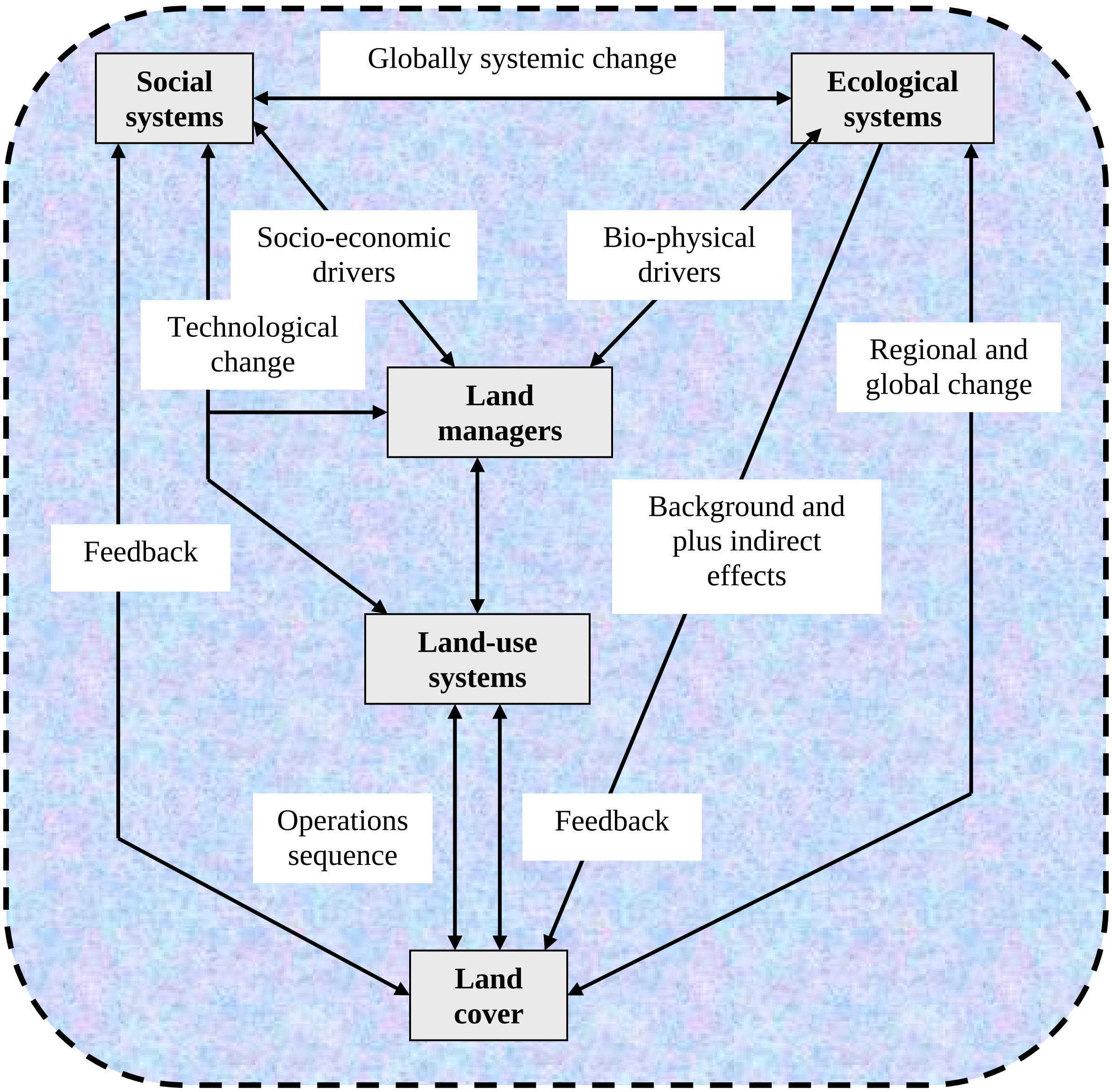


Figure 2.9: Framework for understanding land-use/cover situations (adapted from ***Turner et al. 1995***)

(4) ***Recent Forest-Cover Changes***

Deforestation, one of the most commonly recognized forms of land-cover change, is nevertheless plagued by inconsistencies in definitions (***Williams, 2003***).

The Food and Agriculture Organization (FAO) of the United Nations defines deforestation as occurring when tree canopy cover falls below 10% in natural forests (or when a forest is transformed to other land uses even if tree canopy cover remains higher than 10% – e.g., shifting cultivation). On the basis of this definition, and using country forest inventories, expert estimates, forest-plantation data, and an independent remote sensing survey, the Global Forest Resources Assessment 2000 (***FAO, 2001***) estimated a net decrease in forest area of 9.4 million ha yr^{-1} from 1990 to 2000. This change was a result of a 12.5 million ha yr^{-1} net decrease in natural forests (comprising deforestation of 14.6 million ha yr^{-1}, conversion to forest plantation of 1.5 million ha yr^{-1}, and regeneration of 3.6 million ha yr^{-1}), and 3.1 million ha yr–1 net increase in forest plantations (1.5 million ha yr^{-1} converted from natural forests, and 1.6 million ha yr^{-1} of afforestation). Most of the deforestation occurred in the tropics, while most of the natural forest re-growth occurred in Western Europe and eastern North America; the total net forest change was positive for the temperate regions and negative for the tropics (***Ramankutty et al. 2006***).

(5) ***Recent Changes in Drylands***

Desertification is a difficult process to evaluate because of its varying definitions and perceptions. The United Nation's Convention to Combat Desertification (UNCCD) defines desertification as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities". Land degradation is defined as the decrease or destruction of the biological productivity of the land, including vegetation degradation, water and wind erosion, and chemical and physical deterioration, or a combination of these processes (***Geist, 2005***). The LUCC-MA synthesis of the main areas of degraded drylands was constrained by lack of reliable data. Most available data were heterogeneous in terms of the monitoring methods or the indicators used. The study found that the main areas of degraded dryland lie in Asia. The synthesis did not support the claim that the African Sahel is a desertification "hot spot" at the present time. However, it found major gaps in desertification studies, including around the Mediterranean Basin, in eastern Africa, in parts of South America (in northern Argentina, Paraguay, Bolivia, Peru and Ecuador) and in the United States of America. If dryland degradation data were available in compatible format for all the continents, the global distribution of the most degraded drylands could be different, but the patterns observed in Asia would most likely remain the same (***Ramankutty et al. 2006***).

As shown in **Table 2.13**, in the USA the most commonly used land cover classification system is the USGS land use and land cover classification system for use with remote sensor data (***Anderson et al. 1976***). Most projects use the top classes of the Anderson scheme and define lower classes based on the needs of the specific project (***Jensen, 2007***). There are many other classification schemes in use by programmes such as the USFWS National Wetlands Inventory, the USGS GAP Analysis Program and the NOAA Coast watch Change Analysis Program (***Jensen, 2007***). Most of these classification systems have subclasses that can still be aggregated into the upper classes of the USGS Anderson Classification System (**Figures 2.10 and 2.11; *Purkis and Klemas, 2011***).

Table 2.13: USGS **Anderson et al. (1976)** Land Use and Land cover Classification System for use with Remote Sensor Data (adapted from ***Purkis and Klemas, 2011***)

Level I	**Level II**
1 Urban or Built-Up Land	11 Residential
	12 Commercial and services
	13 Industrial
	14 Transportation, communications and utilities
	15 Industrial and commercial complexes
	16 Mixed urban or built-up land
	17 Other urban or built-up Land
2 Agricultural Land	21 Cropland and pasture
	22 Orchards, groves, vineyards, nurseries and ornamental horticultural areas
	23 Confined feeding operations
	24 Other agricultural land
3 Rangeland	31 Herbaceous rangeland
	32 Shrub-brush land rangeland
	33 Mixed rangeland
4 Forest Land	41 Deciduous forest land
	42 Evergreen forest land
	43 Mixed forest land
5 Water	51 Streams and canals
	52 Lakes
	53 Reservoirs
	54 Bays and estuaries
6 Wetland	61 Forested wetland
	62 Non-forested wetland
7 Barren Land	71 Dry salt flats
	72 Beaches
	73 Sandy areas other than beaches
	74 Bare exposed rock
	75 Strip mines, quarries, and gravel pits
	76 Transitional areas
	77 Mixed barren land
8 Tundra	81 Shrub and brush tundra
	82 Herbaceous tundra
	83 Bare ground tundra
	84 Wet tundra
	85 Mixed tundra
9 Perennial Snow or Ice	91 Perennial snowfields
	92 Glaciers

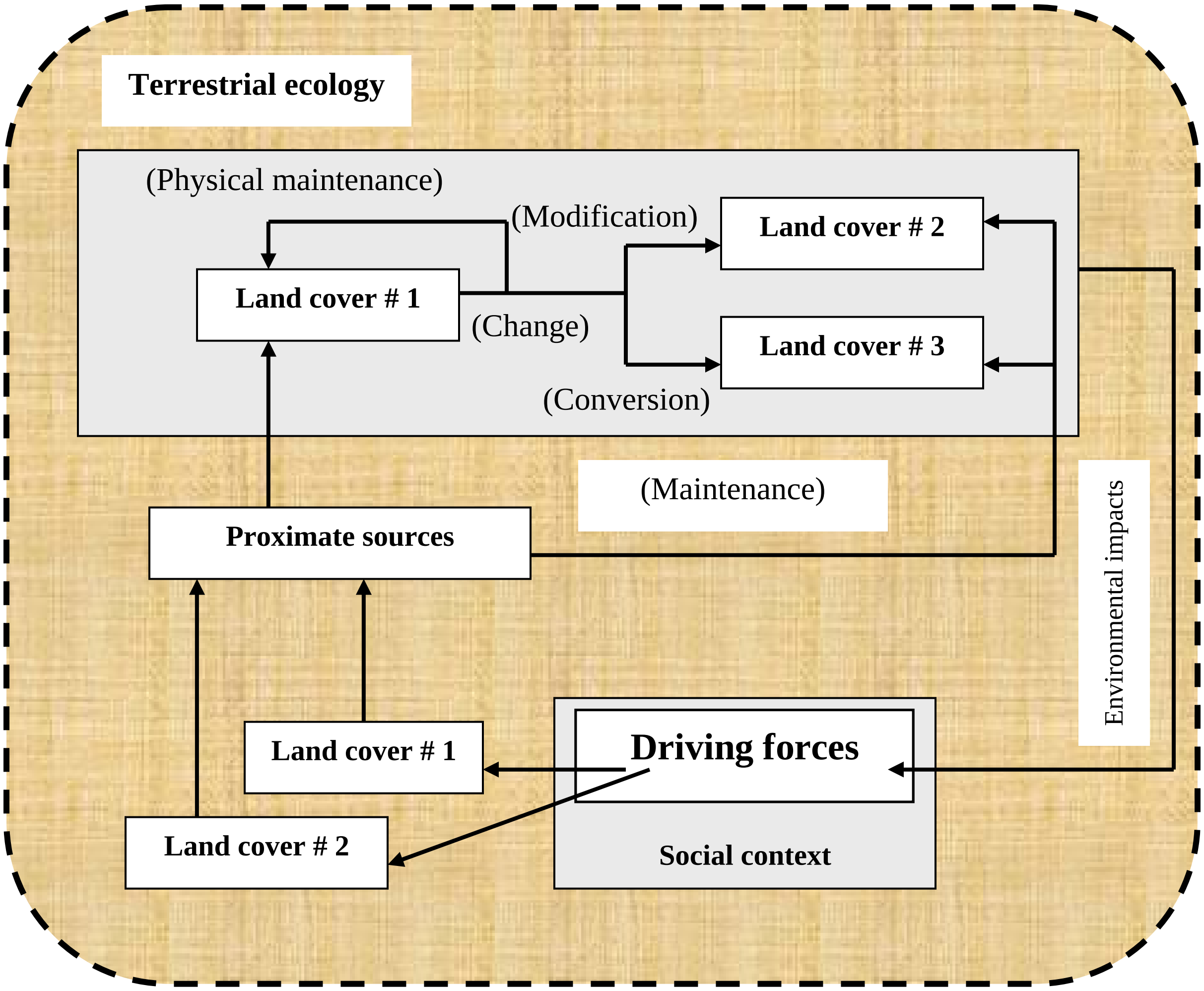


Figure 2.10: Links between human activities and land use and land cover (adapted ***Ojima et al. 1994***)

2.2.12 *Climate Changes and Bioenergy*

Bioenergy is a composite word, combining “biomass” and “energy”. Bioenergy is the production of heat, power and liquid fuels (termed biofuels) from biomass. Biomass is plant matter or derived from plant matter, and can be sourced from processing and post-consumer residues, in-field residues from forestry and agriculture, and purpose-grown energy crops. It could be considered that the impacts on soil health of the latter two sources of biomass. The potential for bioenergy to mitigate climate change is a major driver of the recent policy development and industry expansion. Following the Intergovernmental Panel on Climate Change (IPCC) definition, it could be defined climate change as a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (***IPCC, 2001***).

Traditional biofuels (e.g., wood, crop residues, animal dung) have been used as sources of household energy (such as for cooking and heating) since the dawn of human civilization. Modern biofuels go back to 1896 when Henry Ford's first car was designed to run on ethanol. They achieved prominence during the oil embargo of the 1970s. However, the current interest in biofuels is driven by high energy demands and the impacts of fossil fuel combustion on emissions of CO_2, CH_4, and N_2O with the attendant changes in climate. Global energy consumption is expected to grow by 50% between 2005 and 2030. From its humble beginning in the late 19th and early 20th centuries, fuel ethanol production in the United States grew to 310 million liters (ML) in 1980, 2.3 billion liters (BL) in 1985, 2.8 BL in 1990, 4.9 BL in 1995, 6.3 BL in 2000, 15.4 BL in 2005, and 25.9 BL in 2007 (***Lal and Stewart, 2010***).

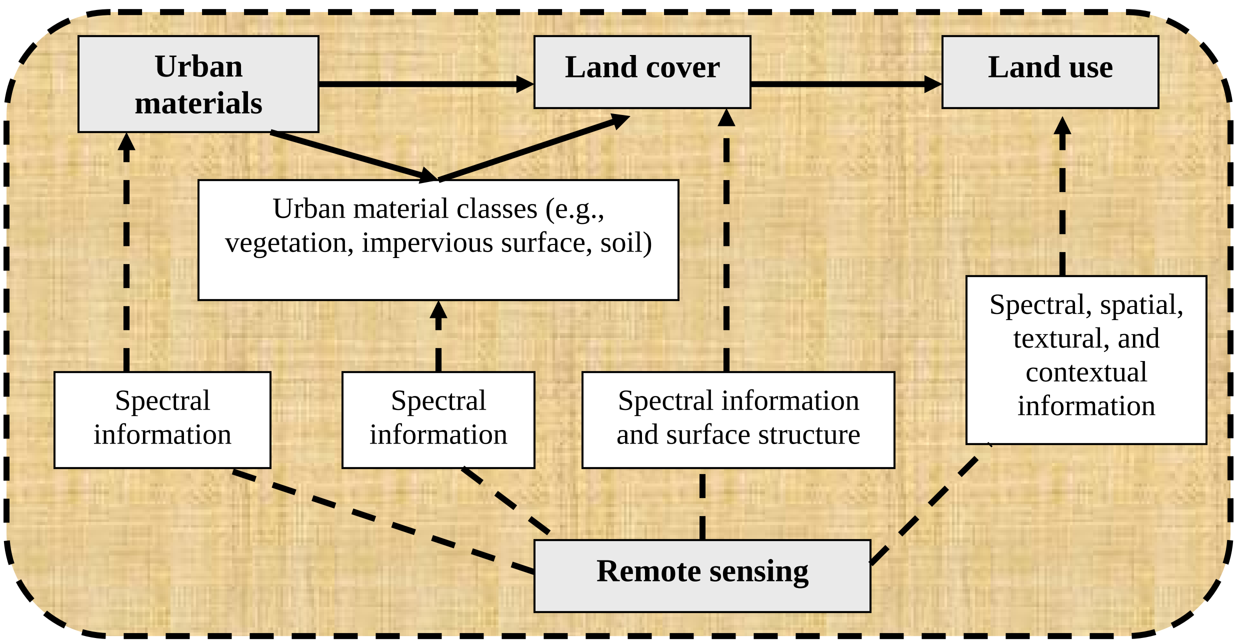


Figure 2.11: Relationship among remote sensing of urban materials, land cover, and land use, a conceptual framework (adapted from ***Weng and Lu, 2009***)

As the world searches for low-carbon renewable energy, there will be significant opportunities for biomass to provide heat, electricity and transport fuels. Bioenergy can contribute to climate change mitigation through increasing sequestration of carbon (e.g. in forests) and through reducing use of fossil fuels. With various feedstocks and process routes and multiple products, there are many bioenergy options that can produce not only energy but also other products, such as biochar, that may enhance the economic, social and environmental role of bioenergy. Bioenergy could supply greater than 30% of world primary energy demands by 2050. However, questions remain concerning the capacity and sustainability of large-scale intensive biomass energy systems, particularly over implications for soil health (***Muller, 2009***).

The major policy driver for the current promotion of bioenergy is its potential to contribute to climate change mitigation. Bioenergy systems can displace the use of fossil fuel, leaving the fossil fuel "in the ground", and may sequester carbon (through storage of carbon in the soil or vegetation). The potential benefit from increasing biomass energy (stationary and transport) and avoiding fossil fuel use is significant. The IPCC estimates that by 2030, increased energy generation efficiency and switching to alternative low-carbon sources including bioenergy could reduce emissions by approximately 1.6–2.5 Gt CO_2-e per annum for light transport (***Ribeiro et al. 2007***), and between 2.0 and 4.2 Gt CO_2-e per annum for stationary energy production (***Sims et al. 2007***).

Also important are the production-chain emissions, due to: fossil fuel use, for example, in cultivation, harvest, transport, fertiliser manufacture; non-CO_2 emissions, such as nitrous oxide (N_2O) from applied fertiliser; and change in biomass and soil carbon. Co-products can also have a significant impact on the GHG balance of some bioenergy systems: biochar, a co-product of pyrolysis, can be used as a soil amendment improving soil health and yielding mitigation benefits (***Cayuela et al. 2010***); residues from ethanol and biodiesel production can be used as animal feeds, saving emissions associated with feed production (***Dale et al. 2010***). Land use change (LUC), both direct and indirect, can significantly add to the production-chain emissions of bioenergy systems (***George and Cowie, 2011***).

While climate change is a major driver for the industry, mitigation value must be balanced with other objectives. This becomes a challenge for policy development and implementation, as there are often trade-offs: maximizing carbon sequestration and biomass production may reduce potential biodiversity benefits, or adversely impact hydrology. However, there are potential "win–win" scenarios where mitigation, conservation and production objectives can be addressed simultaneously, for example, the development of a mallee industry for bioenergy production in Western Australia (***Bartle et al. 2007***). To make a significant contribution to climate change mitigation, a huge quantity of biomass will be required (***Bauen et al. 2010***). For example, it is estimated that for the USA to produce 30% of their domestic transport fuel demand would require the growing and processing of approximately one billion tonnes of biomass per annum (***Perlack et al. 2005***). The potential impact on GHG emissions of large-scale bioenergy systems will require carefully developed policy to meet multiple objectives and optimize production.

Bioenergy generally costs significantly more than existing fossil fuel-based energy sources, but it is promoted for various reasons including:

- Energy security;

- Environmental benefits, particularly mitigation of climate change;
- Rural and regional development;
- Human health (***Duer and Christensen 2010***).

The development of bioenergy is encouraged by policies including renewable energy targets, industry development grants and emissions trading (***Capon et al. 2010***). However, there are concerns about potential impacts of the expansion and intensification of large-scale bioenergy systems including:

- The "food versus fuel" debate – it has been asserted that utilization of food for fuel [particularly corn (*Zea mays*) for ethanol] has led to rising food prices (***Pimentel et al. 2009***), but others claim that this impact has been exaggerated (***Baffes and Haniotis 2010***) or can be avoided by integrating food, feed and biomass production (***Dale et al. 2010***). Nevertheless, the stronger competition for resources as the human population grows could be a significant challenge for future bioenergy development (***Bartle and Abadi 2010***).
- The actual net GHG balance of bioenergy systems – some systems may deliver minimal GHG savings, when production-chain emissions and impacts on terrestrial carbon stocks are accounted (***Tyner et al. 2010***).
- Indirect land use change (iLUC) – use of agricultural land for biomass production may lead indirectly to deforestation, with implications for soil health and climate change (***Delucchi, 2010***).
- Local environmental impacts – for example, impacting air quality due to increased emissions in production of energy from biomass crops and biofuel refining; reduced water supply where production of biofuels uses significant water; and soil health (***Lasch et al. 2010***; ***George and Cowie, 2011***).

2.2.13 *More uncertainty for agriculture under climate change*

The issues of agricultural production are complicated by increasing climate uncertainty. The relationship between agriculture and climate change is complex. Agriculture contributes to global warming through emissions of methane and nitrous oxide. Changes in land use practices (management of cropland and grazing land) are considered to be the best mitigation options (***IPCC, 2007b***). Agriculture is also extremely sensitive to climate change, and it is anticipated that large areas of croplands, in particular in semi-arid zones, will need to adapt to new conditions with lower precipitation. Climate change is expected to alter hydrologic regimes and patterns of freshwater resource availability, with impacts on both rainfed and irrigated agriculture (***FAO, 2008b***). Severe reductions in river runoff and aquifer recharge are expected in the Mediterranean basin and in the semi-arid areas of Southern Africa, Australia and the Americas, affecting water availability for all uses. The projected increase in the frequency of droughts and floods will hurt crop yields and livestock, with greater impacts coming earlier than previously predicted

(***IPCC, 2007a***).While climate change does not seem to threaten global food production; it will alter the distribution of agricultural potential. Most of the increase in cereal production will be concentrated in the Northern Hemisphere, while more frequent and severe droughts and floods will hurt local production, especially in subsistence sectors at low latitudes (***IPCC, 2007c***). Several densely populated farming systems in developing countries are at risk from the impacts of climate change. A combination of reduced river base flows increased flooding and rising sea levels is expected to impact highly productive irrigated systems that help maintain the stability of cereal production. The production risks will be amplified in alluvial plains dependent on glacier melt (Colorado, Punjab) and, in particular, in lowland deltas (the Ganges and Nile) (***Connor et al. 2009***).

2.2.14 *The Toxicology of Climate Changes*

The U. N. Intergovernmental Panel on Climate Change (IPCC) has completed four assessments covering the evidence, impacts, and mitigation of climate change (***IPCC, 2007a,b,c***). They report unequivocal global warming with evidence of increases in global mean air and ocean temperatures, widespread snow and ice melt, and rising global sea level. Temperature is projected to increase 1.8–4.0 °C by the end of the century under a range of probable greenhouse gas emission scenarios with the greatest warming expected at high latitudes. In addition to global warming, some regions, such as North and South America, northern Europe, and northern and central Asia are projected to experience increased precipitation, while others, including southern Africa and Asia and the Mediterranean, are expected to experience substantial droughts. Heat waves, precipitation and storm events are predicted to be more frequent and intense. Oceanic acidification linked to increasing atmospheric carbon dioxide levels is a growing threat to marine organisms and ecosystems (***Noyes et al. 2009***).

Climate change will have a powerful effect on the environmental fate and behavior of chemical toxicants by altering physical, chemical, and biological drivers of partitioning between the atmosphere, water, soil/sediment, and biota, including: air-surface exchange, wet/dry deposition, and reaction rates (e.g., photolysis, biodegradation, oxidation in air). Temperature and precipitation, as altered by climate change, are expected to have the largest influence on the partitioning of chemical toxicants. In addition, an array of important processes, such as snow and ice melt, biota lipid dynamics, and organic carbon cycling, will be altered by climate change potentially producing significant increases in fugacity (thermodynamic measure of substance tendency to prefer one phase over another) and contaminant concentrations (***MacDonald et al. 2002***).

The IPCC projects that climate change is likely to affect the health of millions of people, and that the effects will be mostly negative (***Confalonieri et al. 2007***). The elderly, infants, children, and urban poor are expected to be most vulnerable to the rapidly changing climate (***Confalonieri et al. 2007; Ebi et al.***

2006; Patz et al. 2005). Notable adverse consequences of climate change on human health include increased death and injury associated with more severe and frequent heat waves, extreme weather events, and enhanced vector-borne and allergic disease transmission. While adverse health outcomes are projected to be greatest in low-income countries, more severe, frequent, and widespread heat waves and storm events will also impact developed countries unprepared to cope with these events (***Confalonieri et al. 2007***).

Table 2.14: Climate change-induced effects of contaminants on human health (adapted from ***Noyes et al. 2009***)

Climate change-induced effect	***Relationships/Interactions***	***References***
Increased cardio-respiratory disease	↑ temperature exacerbates the adverse effects of ozone and PM The elderly and individuals with pre existing cardio-respiratory disease may be more vulnerable to these effects	Bell et al. 2007; Confalonieri et al. 2007; Dominici et al. 2006; Fiala et al. 2003; IPCC, 2007a; Knowlton et al. 2004; Koken et al. 2003; Mauzerall et al., 2005; Ordonez et al. 2005; Ren and Tong, 2006
Altered exposure and risk	Some populations may experience increases or decreases in POP exposures and health risks depending on the region and diet of exposed individuals Pesticides may impair mechanisms of temperature regulation especially during times of thermal stress	Bard, 1999; Gordon, 1997; McKone et al. 1996; Watkinson et al. 2003
Increased susceptibility to pathogens	Toxicants can suppress immune function, and climate-induced shifts in disease vector range will result in novel pathogen exposure human vulnerability to climate shifts in pathogens Immune system impairment linked to toxicants may increase Low-income populations, infants, children, and the chronically ill may be more susceptible	Abadin et al. 2007; Haines et al. 2006; Lipp et al. 2002; Nagayama et al. 2007; Patz et al. 2005; Rogers and Randolph, 2000; Smialowicz et al. 2001
Increased allergenicity potential	Air pollution and allergen exposures linked to climate change can exacerbate allergic disease and asthma incidences Climate change enhanced allergen production coupled with POP exposures may sensitize individuals to allergic disease Low-income populations, infants, children, and the chronically ill may be more susceptible	D'Amato et al. 2002; Diaz-Sanchez et al. 2003; Epstein, 2005; Janssen et al. 2003

There continues to be a lack of data describing the effects of contaminant exposures on human health and vulnerable subpopulations under projected climate change scenarios. However, a number of studies suggest that the toxicity of ozone and particulate matter (PM) will be exacerbated with global warming, and some of these data support that older adults will be especially vulnerable (***Bell et al. 2007;***

Confalonieri et al. 2007; Dominici et al. 2006; Fiala et al. 2003; IPCC, 2007c). Other potential interactions between climate change and toxicant exposure include increased susceptibility to pathogens (***Abadin et al. 2007; Nagayama et al. 2007***) and aeroallergens (***Epstein, 2005; Janssen et al. 2003***). **Table 2.14** summarizes important interactions between climate change, toxicant exposures, and human health (***Noyes et al. 2009***).

2.3 *Climate Applications and Agriculture*

Climate variability creates risk in rainfed farming. Risk in turn discourages investment by farmers, governments and development agencies. For instance, in dry regions recurrent droughts debilitate and destabilize poor, agricultural-based societies, and contribute to land degradation by reducing vegetative cover and water supplies. Drought triggers the exploitation of diminishing resources in order to survive. Climate change caused by global warming is likely to increase the frequency of climatic extremes in the future and result in changes in cropping practices and patterns over time and space. If climate variability could be predicted in advance, it would help societies prepare for and cope with the resultant shocks. As well, since drought is a trigger for desertification, better drought prediction and monitoring could help prevent land degradation (***Shapiro et al. 2007***).

In light of population growth and climate change, investment in agriculture is the only way to avert wide-scale food shortages or, in the worst-case scenario, catastrophic human suffering. Assuming investment is forthcoming, maintaining food security will require crop scientists to integrate and apply a broad range of strategies. These include tried and tested technologies such as conventional breeding and agronomy as well as new approaches such as molecular genetics and conservation agriculture. Examples of successful applications as well as future prospects of how each discipline can be expected to evolve over the next 30 years are presented (***Reynolds, 2010***).

The Intergovernmental Panel on Climate Change (***IPCC, 2009***) indicates that rising temperatures, drought, floods, desertification and weather extremes will severely affect agriculture, especially in the developing world. While the convergence of population growth and climate change threatens food security on a worldwide scale, the opportunity also exists to address the pernicious threat of famine. Indeed the prerequisites to develop a globally coordinated effort to ensure long-term food security are available for the first time in human history. Namely: **(i)** the realization that agricultural problems worldwide have a common scientific basis; **(ii)** a vast and expanding database encompassing all disciplines that impinge on agricultural productivity; **(iii)** a de facto network of agricultural scientists working in almost every country in the world; and **(iv)** unprecedented opportunities for communication, data analysis and investment. These elements, the indisputable fruits of an industrialized global economy, were not available to our predecessors, which is probably why climate change in history spelt death.

Agricultural researchers worldwide are, therefore, working to mitigate these and other effects of climate change to increase productivity within a finite natural resource basis. Assuming investment is forthcoming, maintaining food security in the face of population growth and climate change will require a holistic approach that includes stress-tolerant germplasm, coupled with sustainable crop and natural resource management as well as sound policy interventions. There will be duplication of effort as regions struggle with parallel challenges; however, judicious public investment can reduce redundancy of effort permitting local organizations to focus on adaptive research **(*Reynolds and Ortiz, 2010*)**.

2.3.1 *Adaptation: Living with Climate Changes*

Adaptation is an automatic or planned response to change that minimizes the adverse effects and maximizes any benefits. It is one of the two possible means of coping with human-induced climate change and sea-level rise. The other option is to reduce the magnitude of human-induced climate change by reducing greenhouse gas emissions. This is called *mitigation*. Adaptation is essential to cope with the climate change and sea-level rise that we cannot avoid now and in the near future, while mitigation would limit the extent of future climate change. Adaptation is essentially a local challenge, while mitigation is essentially a global process that will only be achieved by international cooperation and a common commitment. Adaptation is necessary because climate change is already happening, and the long lag times in the climate system make further climate change, and especially sea-level rise, inevitable. Further climate change is already built into the system by past greenhouse gas emissions, that is, we are already committed to it. The effect happens decades to centuries after the cause and cannot readily be stopped. Additional to the existing commitment to climate change, even more climate change is made inevitable by the long time, at least several decades, between *deciding* to reduce emissions, and the socioeconomic system changing enough to *actually* reduce greenhouse gas emissions sufficiently to stop making the situation worse. Very substantial reductions in greenhouse gas emissions will be necessary before greenhouse gas concentrations stop going up. In fact, for centuries to come, atmospheric CO_2 concentrations will not fall much below whatever maximum levels are reached, even after major reductions in emissions unless we actively withdraw greenhouse gases out of the atmosphere. This is due to the large reservoirs of CO_2 in the ocean, soil and biosphere, which are in equilibrium with the atmosphere on a time-scale of decades. The permanent sinks are much slower to act. In short, we cannot simply turn off climate change, so we must learn to live with it. That is why adaptation is essential (***Pittock, 2009***).

Studies indicate that Africa's agriculture is negatively affected by climate change (***McCarthy et al. 2001***). Adaptation is one of the policy options for reducing the negative impact of climate change (***Adger et al. 2003; Kurukulasuriya and Mendelsohn, 2008***). Common adaptation methods in agriculture include use of new crop varieties and livestock species that are better suited to drier conditions, irrigation, crop diversification, adoption of mixed crop and livestock farming systems, and changing planting dates (***Bradshaw et al. 2004; Nhemachena and Hassan, 2007; Kurukulasuriya and Mendelsohn, 2008***).

A handbook on methods for climate change impacts assessment and adaptation strategies has been developed by the United Nations Environment Program (***UNEP, 1998; Brooks et al. 2005; Lim et al. 2005; Pittock, 2009***). The handbook discusses the principles and strategies for adaptation. These can be summarized in eight alternative but not exclusive strategies:

(1) ***Bear losses***: This is the baseline response of 'doing nothing'. Bearing loss occurs when those affected have failed to act until it is too late, or have no capacity to respond in any other way (for example, in extremely poor communities) or where the costs of adaptation measures are considered to be high in relation to the risk or the expected damages. The big problem with this solution is that losses may become unbearable.

(2) ***Share losses***: This involves a wider community in sharing the losses. Sharing takes place in traditional societies and in the most complex, high-tech societies. In traditional societies, mechanisms include sharing losses with extended families, villages or similar small-scale communities. In societies organized on a larger-scale, losses are shared through emergency relief, rehabilitation, and reconstruction paid for by government funds or public appeals, or through private insurance. However, insurance usually applies only when the risk is considered random and uncertain for the individual insured, not when it is predictable. Even with shared losses, the accumulated loss to society may eventually become unacceptable, at which point other actions must be taken.

(3) ***Modify the threat***: For some risks, it is possible to exercise a degree of control over the specific environmental threat. For 'natural' events such as a flood or drought, possible measures include flood control works (dams, dikes, levees) or water storages. For climate change, attempts to modify the threat through such measures may quickly become too expensive, and the more sensible modification to reduce the threat is to slow the rate of climate change by reducing global greenhouse gas emissions and eventually stabilizing greenhouse concentrations in the atmosphere. (Note, however, that in Intergovernmental Panel on Climate Change (IPCC) terminology, measures that reduce climate change are referred to as 'mitigation' of climate change, in distinction to 'adaptation', which is reserved for an optimal response to a given climate change.)

(4) ***Prevent effects***: A frequently used set of adaptation measures involves steps to prevent the effects of climate change and variability. Examples for agriculture would be changes in crop management practices such as increased irrigation, additional fertilizer, and pest and disease control.

(5) ***Change use***: Where the threat or reality of climate change makes the continuation of an economic activity impossible or extremely risky, consideration can be given to changing the use. For example, a farmer may choose to switch to crop varieties more adapted to lower soil moisture. Similarly, agricultural land may be returned to pasture or forest or other uses may be found such as recreation, tourism, wildlife refuges, or national parks.

(6) ***Change location***: A more extreme response is to change the location of economic activities. For example, major crops and farming regions could be relocated away from areas of increased aridity and heat to areas that are currently cooler and which may become more attractive for some crops in the future. This may be possible in some countries, but not in others where migration to cities or other countries may be the only alternatives.

(7) ***Research***: Possibilities for adaptation can also be opened up by research into new technologies and methods of adaptation, such as greater water use efficiency, cheap water desalinization, or new crop cultivars.

(8) ***Educate, inform, and encourage behavioral change***: Dissemination of knowledge through education and public information campaigns can lead to adaptive behavioral change. Such activities have been little recognized and given little priority in the past, but are likely to assume increased importance as the need to involve more communities, sectors, and regions in adaptation becomes apparent. Water conservation and fire prevention campaigns and regulations are already major adaptive trends in countries such as Australia. Discouragement of maladaptive trends such as development in low-lying coastal areas is another useful strategy. This may involve planning rules or other 'carrots and sticks'.

2.3.2 *Remote-Sensing and GIS Applications in Agrometeorology*

A picture is worth a thousand words. Is this true, and if so, why? Pictures concisely convey information about positions, sizes, and interrelationships between objects. By their nature, they portray information about things that we can recognize as objects. These objects in turn can convey deep levels of meaning. Because humans possess a high level of proficiency in deriving information from such images, we experience little difficulty in interpreting even those scenes that are visually complex. We are so competent in such tasks that it is only when we attempt to replicate these capabilities using computer programs; for instance, that we realize how powerful our abilities are to derive this kind of intricate information. Each picture, therefore, can truthfully be said to distill the meaning of at least a thousand words (***Campbell and Wynne, 2011***).

It is well known that, geographic information system (GIS) is a computer technology that uses a geographic information system as an analytic framework for managing and integrating data; solving a problem; or understanding a past, present, or future situation. GIS is, therefore, about modelling and mapping the world for better decision making. Remote sensing is the acquisition of information about an object or phenomenon, without making physical contact with the object. In modern usage, the term generally refers to the use of aerial sensor technologies to detect and classify objects on Earth (both on the surface, and in the atmosphere and oceans) by means of propagated signals (e.g. electromagnetic radiation emitted from aircraft or satellites).

The Earth's climate is now clearly changing and getting warmer. Many components of the climate system are changing at rates and in patterns that are not natural and are best explained by the increased atmospheric abundances of greenhouse gases and aerosols generated by human activity during the 20th century. These changes include temperatures of the atmosphere, land and ocean; the extent of sea ice and mountain glaciers; the sea level; the distribution of precipitation; and the length of the seasons (***AGU, 2008***).

The Earth has warmed consistently and unusually over the past few decades in a manner that can be explained only when a greenhouse process is overlaid on orbital variation, solar variation, volcanic eruptions and other natural disturbances. Observational evidence, complex modelling and simple physics all confirm this. Whatever the proportion of human-induced rise in global temperature versus natural rise, there is no doubt that the temperature and the sea level are rising, the Greenland and Antarctic ice sheets are disintegrating, and major weather patterns and ocean currents are shifting. The Earth's warming is already causing severe droughts and flooding, major vegetation transformations in deserts and forests, massive tundra methane releases and the degradation of the Amazon rainforest and Saharan vegetation. It is also starting to impact the Indian Ocean Monsoon, the Atlantic Conveyor Belt and El Niño weather patterns. The economic impacts of droughts in the USA alone cause $68 billion in losses per year (***Purkis and Klemas, 2011***).

Remote sensing is now a mature enough technology to answer some of the fundamental questions in global environmental change science, namely:

- How and at what pace is the Earth system changing and what are the forces causing these changes?
- How does the Earth system respond to natural and human-induced changes?
- How well can we predict future perturbations to the Earth system and what are the consequences of change to human civilization?

Ice sheets, ocean currents and temperatures, deserts and tropical forests each have somewhat different remote sensing requirements. For instance, ocean temperatures are measured by thermal infrared sensors, while ocean currents, winds, waves, and sea level require various types of radar instruments on satellites. Most ocean features are large and require spatial resolutions of kilometers, while observations of desert or forest changes may require resolutions of tens of meters and many bands within the visible and near-infrared region of the electromagnetic spectrum. Monitoring of coral bands pooled in the short-wavelength visible spectrum. Fortunately, by the turn of this century, most of these requirements had been met by NASA (the National Aeronautics & Space Administration) and NOAA (the National Oceanic & Atmospheric Administration) satellites and aircraft, the European Space Agency (ESA) and the private sector (***Jensen, 2007***). Furthermore, new satellites are being launched, carrying imagers with fine spatial (0.64 m) and spectral (200 narrow bands) resolutions, as well as other environmental sensors. These provide a capability to detect changes in both the local and the global environment even more accurately. For the first time, constellations of satellites are being launched with the sole aim of quantifying aspects of the Earth's climate synergistically. With such technology available, governments are no longer alone in being able to monitor the extent of tropical forests and coral reefs, the spread of disease and the destruction caused by war (***Purkis and Klemas, 2011***).

The technology of remote sensing evolved gradually into a scientific subject after World War II. Its early development was driven mainly by military uses. Later, remotely sensed data became widely applied for civil applications. The range of remote sensing applications includes archaeology, agriculture, cartography, civil engineering, meteorology and climatology, coastal studies, emergency response, forestry, geology, geographic information systems, hazards, land use and land cover, natural disasters, oceanography, water resources, and so on. Most recently, with the advent of high spatial resolution imagery and more capable techniques, urban and related applications of remote sensing have been rapidly gaining interest in the remote sensing community and beyond (***Weng, 2010***).

Advances in the application of Geographical Information Systems (GIS) and the Global Positioning System (GPS) help to incorporate geo-coded ancillary data layers in order to improve the accuracy of satellite image analysis. When these techniques for generating, organizing, sorting and analyzing spatial information are combined with mathematical climate and ecological models, scientists and managers can improve their ability to assess and predict the impact of global environmental changes and trends (***Lunetta and Elvidge, 1998***).

To handle the vast quantities of information being generated by today's Earth observation programmes, there have been significant advances made in the use of the Internet to store and disseminate geospatial data to scientists and the public. The Internet is set to play an even greater role in the handling of products delivered by future missions. It well established that, the Earth's climate is getting warmer and the patterns of the weather and ocean currents are changing. Severe droughts and flooding are becoming more prevalent and the ice sheets of Greenland and at the poles are disintegrating. The global sea level is rising by about 2 to 3 mm per year, threatening to inundate many coastal areas by the end of this century. Remote sensors on satellites offer an effective way for monitoring environmental trends on a global scale. They can detect physical and biological changes in the atmosphere, in the oceans and on land. Satellite systems have become the defining technology in our ability to quantify global change. The accuracy and applicability of satellite imagery is constantly improving due to technological advances, such as finer spectral/spatial resolution, more powerful computers, the Global Positioning System (GPS) and Geographical Information Systems (GIS). When these techniques for generating, organizing and analyzing spatial information are combined with mathematical and environmental models, scientists and managers have a means for assessing and predicting the impact of global environmental changes (***Purkis and Klemas, 2011***). It could be explained the following items:

Remote sensing concepts:

The field of remote sensing has been defined many times (**Table 2.15**). Examination of common elements in these varied definitions permits identification of the topic's most important themes. From a cursory look at these definitions, it is easy to identify a central concept: the gathering of information at a distance. This excessively broad definition, however, must be refined if it is to guide us in studying a body of knowledge that can be approached in a single course of study. This definition of **Campbell and Wynne (2011)** serves as a concise expression of the scope of this volume. It is not, however, universally applicable, and is not intended to be so, because practical constraints limit the scope of this volume. So, although this text must omit many interesting topics (e.g., meteorological or extraterrestrial remote sensing), it can review knowledge and perspectives necessary for pursuit of topics that cannot be covered in full here. The scope of the field of remote sensing can be elaborated by examining its history to trace the development of some of its central concepts. A few key events can be offered to trace the evolution of the field (**Table 2.16 and Figure 2.12**).

Remote sensing refers to the activities of recording, observing, and perceiving (sensing) objects or events in far-away (remote) places. In remote sensing, the sensors are not in direct contact with the objects or events being observed. Electromagnetic radiation normally is used as the information carrier in remote sensing. The output of a remote sensing system is usually an image representing the scene being observed. A further step of image analysis and interpretation is required to extract useful information from the image. In a more restricted sense, *remote sensing* refers to the science and technology of acquiring information about the earth's surface (i.e., land and ocean) and atmosphere using sensors onboard airborne (e.g., aircraft or balloons) or space borne (e.g., satellites and space shuttles) platforms. Depending on the scope, remote sensing may be broken down into (1) satellite remote sensing (when satellite platforms are used), (2) photography and photogrammetry (when photographs are used to capture visible light), (3) thermal remote sensing (when the thermal infrared portion of the spectrum is used), (4) radar remote sensing (when microwave wavelengths are used), and (5) LiDAR remote sensing (when laser pulses are transmitted toward the ground and the distance between the sensor and the ground is measured based on the return time of each pulse) (***Weng, 2010***).

Remote sensing is primarily concerned with collecting and interpreting information about an object or landscape from a remote vantage point. The platform can be anywhere, ranging from a balloon just above the surface of the Earth to a satellite hundreds of kilometres away in space. Examples of remote sensing include aerial photography, satellite imagery, radar altimetry and laser bathymetry. Coupled with ground measurements, remote sensing can provide valuable information about the surface of the land, the oceans and the atmosphere. Techniques for acquiring aerial photographs were already developed in the 1860s; however, color and color-infrared (CIR) aerial photographs were not widely used until the 1940s and 1950s. The 1950s and 1960s marked the appearance of remote sensing applications for airborne radar and video technologies. A significant event in terms of land remote sensing was the 1972 launch of the first Landsat satellite, originally called ERTS-1. The satellite was designed to provide frequent broad-scale observations of the Earth's land surface. Since 1972, additional Landsat satellites have been put into orbit. Other countries, including France, Japan, Israel, India, Iran, Russia, Brazil, China, and perhaps North Korea, have also launched satellites whose onboard sensors provide digital imagery on a continuous basis (***Purkis and Klemas, 2011***).

The appearance of geographic information systems (**GIS**) in the mid- 1960s reflects the progress in computer technology and the influence of quantitative revolution in geography. GIS has evolved dramatically from a tool of automated mapping and data management in the early days into a capable spatial data-handling and analysis technology and, more recently, into geographic information science (**GISc**). The commercial success since the early 1980s has gained GIS an increasingly wider application. Therefore, to give GIS a generally accepted definition is difficult nowadays. GIS today is far broader and harder to define. Many people prefer to define its domain as geographic information science and technology (**GIS & T**), and it has become imbedded in many academic and practical fields. The GIS & T field is a loose coalescence of groups of users, managers, academics, and professionals all working with geospatial information. Each group has a distinct educational and "cultural" background. Each identifies itself with particular ways of approaching particular sets of problems. GIS has been called or defined as an enabling technology because of the breadth of uses in the following disciplines as a tool. Disciplines that traditionally have studied the earth, particularly its surface and near surface in either physical or human aspect, include geology, geophysics, oceanography, agriculture, ecology, biogeography, environmental science, geography, global science, sociology, political science, epidemiology, anthropology, demography, and many more (***Weng, 2010***).

Table 2.15: Remote sensing: some definitions (cited from ***Campbell and Wynne, 2011***)

Definition	*Citation*
Remote sensing has been variously defined but basically it is the art or science of telling something about an object without touching it.	Fischer et al. (1976)
Remote sensing is the acquisition of physical data of an object without touch or contact.	Lintz and Simonett, (1976)
Imagery is acquired with a sensor other than (or in addition to) a conventional camera through which a scene is recorded, such as by electronic scanning, using radiations outside the normal visual range of the film and camera—microwave, radar, thermal, infrared, ultraviolet, as well as multispectral, special techniques are applied to process and interpret remote sensing imagery for the purpose of producing conventional maps, thematic maps, resources surveys, etc., in the fields of agriculture, archaeology, forestry, geography, geology, and others.	American Society of Photogrammetry
Remote sensing is the observation of a target by a device separated from it by some distance.	Barrett and Curtis (1976)
The term "remote sensing" in its broadest sense merely means "reconnaissance at a distance."	Colwell (1966)
Remote sensing, though not precisely defined, includes all methods of obtaining pictures or other forms of electromagnetic records of the Earth's surface from a distance, and the treatment and processing of the picture data. Remote sensing then in the widest sense is concerned with detecting and recording electromagnetic radiation from the target areas in the field of view of the sensor instrument. This radiation may have originated directly from separate components of the target area; it may be solar energy reflected from them; or it may be reflections of energy transmitted to the target area from the sensor itself.	White (1977)
"Remote sensing" is the term currently used by a number of scientists for the study of remote objects (earth, lunar, and planetary surfaces and atmospheres, stellar and galactic phenomena, etc.) from great distances. Broadly defined, remote sensing denotes the joint effects of employing modern sensors, data-processing equipment, information theory and processing methodology, communications theory and devices, space and airborne vehicles, and large-systems theory and practice for the purposes of carrying out aerial or space surveys of the earth's surface.	National Academy of Sciences (1970)
Remote sensing is the science of deriving information about an object from measurements made at a distance from the object, i.e., without actually coming in contact with it. The quantity most frequently measured in present-day remote sensing systems is the electromagnetic energy emanating from objects of interest, and although there are other possibilities (e.g., seismic waves, sonic waves, and gravitational force), our attention is focused upon systems which measure electromagnetic energy.	Landgrebe, quoted in Swain and Davis (1978)
Remote sensing is the practice of deriving information about the Earth's land and water surfaces using images acquired from an overhead perspective, using electromagnetic radiation in one or more regions of the electromagnetic spectrum, reflected or emitted from the Earth's surface.	Campbell and Wynne (2011)

Table 2.16: Milestones in the history of remote sensing (adapted from ***Campbell and Wynne, 2011***)

Year	*Events*
1800	Discovery of infrared by Sir William Herschel
1839	Beginning of practice of photography
1847	Infrared spectrum shown by A. H. L. Fizeau and J. B. L. Foucault to share properties with visible light
1850–1860	Photography from balloons
1873	Theory of electromagnetic energy developed by James Clerk Maxwell
1909	Photography from airplanes
1914–1918	World War I: aerial reconnaissance
1920–1930	Development and initial applications of aerial photography and photogrammetry
1929–1939	Economic depression generates environmental crises that lead to governmental applications of aerial photography
1930–1940	Development of radars in Germany, United States, and United Kingdom
1939–1945	World War II: applications of nonvisible portions of electromagnetic spectrum; training of persons in acquisition and interpretation of airphotos
1950–1960	Military research and development
1956	Colwell's research on plant disease detection with infrared photography
1960–1970	First use of term *remote sensing*
	TIROS weather satellite
	Skylab remote sensing observations from space
1972	Launch of Landsat 1
1970–1980	Rapid advances in digital image processing
1980–1990	Landsat 4: new generation of Landsat sensors
1986	SPOT French Earth observation satellite
1980s	Development of hyperspectral sensors
1990s	Global remote sensing systems, LiDAR

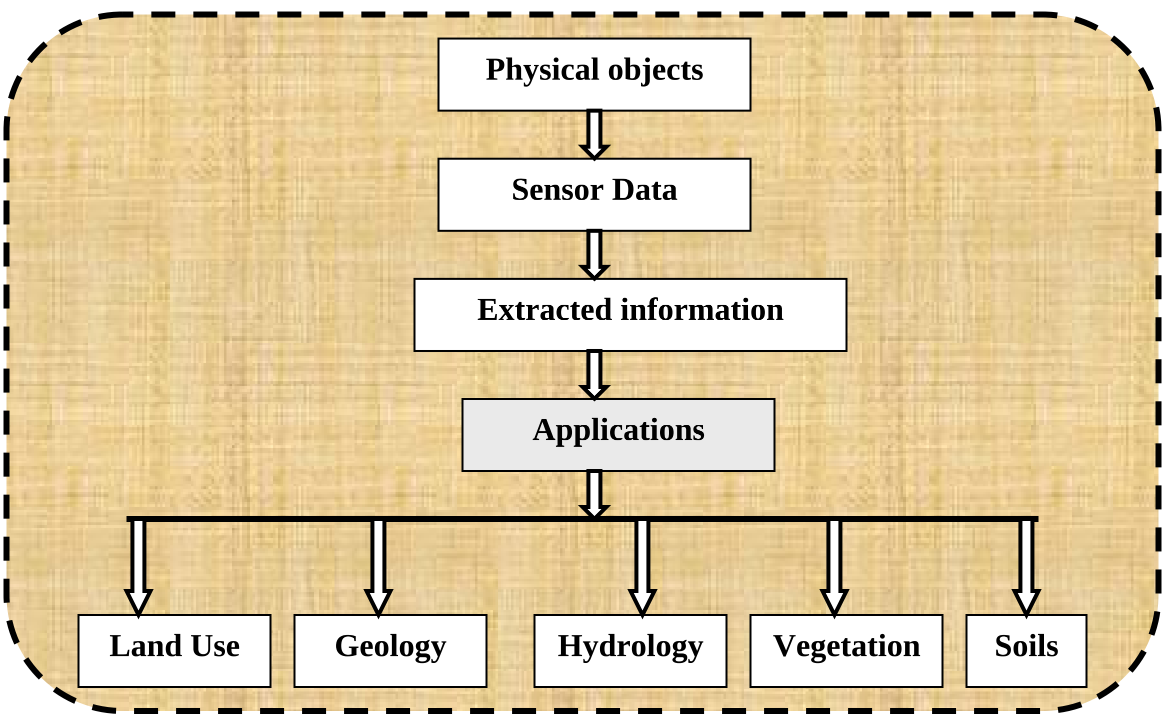


Figure 2.12: Overview of the remote sensing process (adapted from ***Campbell and Wynne, 2011***)

Table 2.17: Units of Length and Frequencies Used in Remote Sensing (adapted from ***Campbell and Wynne, 2011***)

Unit	Distance	Unit	Frequency (cycles per second)
Kilometer (km)	1,000 m	Hertz (Hz)	1
Meter (m)	1.0 m	Kilohertz (kHz)	10^3 (= 1,000)
Centimeter (cm)	0.01 m = 10^{-2} m	Megahertz (MHz)	10^6 (= 1,000,000)
Millimeter (mm)	0.001 m = 10^{-3} m	Gigahertz (GHz)	10^9 (= 1,000,000,000)
Micrometer (μm) [a]	0.000001 m = 10^{-6} m		
Nanometer (nm)	10^{-9} m		
Ångstrom unit (Å)	10^{-10} m		

[a] Formerly called the "micron" (μ); the term "micrometer" is now used by agreement of the General Conference on Weights and Measures.

Remote sensors and systems

It is well known that aerial photography started approximately in 1858 when the famous photographer, Gaspard Tournachon, obtained the first aerial photographs from a balloon near Paris. Since then, aerial photography has advanced, primarily during wartime, first to include color infrared films (for camouflage detection) and later to use sophisticated digital cameras. Aerial photography and other remote sensing techniques are now used successfully in agriculture, forestry, land use planning, fire detection, mapping wetlands and beach erosion, and many other applications. For example, in agriculture it has been used for land use inventories, soil surveys, crop condition estimates, yield forecasts, acreage estimates, crop insect/pest/disease detection, irrigation management and, more recently, precision agriculture (***Jensen, 2007***).

Remote sensing has been used to describe a new field of information collection that includes aircraft and satellite platforms carrying electro-optical and antenna sensor systems since the 1960s. Up to that time, camera systems dominated image collection and conventional photographic media dominated the storage of the spatially varying visible (VIS) and near-infrared (NIR) radiation intensities reflected from the Earth. Beginning in the 1960s, electronic sensor systems were increasingly used for collection and storage of the Earth's reflected radiation and satellites were developed as an alternative to aircraft platforms. Advances in electronic sensors and satellite platforms were accompanied by an increased interest and use of electromagnetic radiant energy, not only from the VIS and NIR wavelength regions, but also from the thermal infrared (TIR) and microwave regions. For instance, the thermal infrared region is used for mapping sea surface temperatures and microwaves (radar) are used for measuring sea surface height, currents, waves and winds on a global scale (***Martin, 2004***).

Remote sensors can be classified by application, wavelength or active/passive mode (**Table 2.18)**. Under applications we have imagers, which produce two-dimensional images and can be used for map-making; radiometers measure the radiant energy in a few specific bands very accurately; while spectrometers provide the energy distribution across a spectral continuum or many spectral bands. Profilers, such as radar and LiDAR, measure the distance to features, allowing us to determine the topography or bathymetry of an area. Radar and LiDAR are primarily ‘active’ devices, since they provide their own pulse of energy. Most other sensors are ‘passive’, because they use electromagnetic energy provided by the sun or the Earth (***Purkis and Klemas, 2011***).

Monitoring Changes in Global Vegetation Cover

Some of the earliest applications of civilian remote sensing have been in agriculture and forestry. The reason for this rich lineage is that chlorophyll, and the plants that contain it, have a distinct, readily detectable spectral signature in the visible and near-infrared portions of the electromagnetic spectrum. Space-and airborne remote sensing systems have therefore been used for many decades to estimate crop health, predict agricultural yield and vegetation vitality, map deforestation and quantify the damage inflicted by disease and insect infestation on crops and forests. Since vegetation is also sensitive to changes in climate, including temperature and rainfall, it can be used as an indicator of global climate change (***Purkis and Klemas, 2011***).

Table 2.18: Classification of remote sensors (adapted from ***Purkis and Klemas, 2011***)

Classification by application	Classification by wavelength	Classification by mode
Imagers (mappers) Photographic (film) Multispectral (array) Radar †Side-scan sonar Radiometers Spectrometers Profilers (rangers) LiDAR, Radar	Visible (array or film) Near infrared (reflected) Thermal infrared (emitted) Microwave †Sound waves †Seismic waves	Active LiDAR Radar †Sonar Passive Visible Infrared Microwave

† Not electromagnetic waves

Plants, by virtue of their chlorophyll content, have a very distinct spectral signature which differs markedly from other land cover types such as soil, water and bare earth **(Figure 2.13)**. The vegetation spectrum has two primary chlorophyll absorption bands in the blue and red regions which are due to pigments such as chlorophyll a, chlorophyll b and β-carotene, which reside in the upper layers of the leaf (palisade parenchyma). By contrast, there is strong reflectance at near-infrared wavelengths, caused by scattering in the spongy mesophyll, the deeper layers of the leaf. In the middle infrared region, three water absorption bands express themselves as a function of how hydrated the leaf tissue is. Thus, if the plant is stressed or drying up, there will be less absorption by the chlorophyll and water bands, as well as less reflection in the near-infrared. The ability of the near-infrared to penetrate deep into a leaf canopy makes it also useful for estimating plant biomass. **Figure 2.13** suggests that it is easy to distinguish vegetated areas from bare ones; however, since the spectra of various plants are somewhat similar, it is not a trivial task to identify plants to the species level on the basis of their spectral signature alone (***Jensen, 2007***).

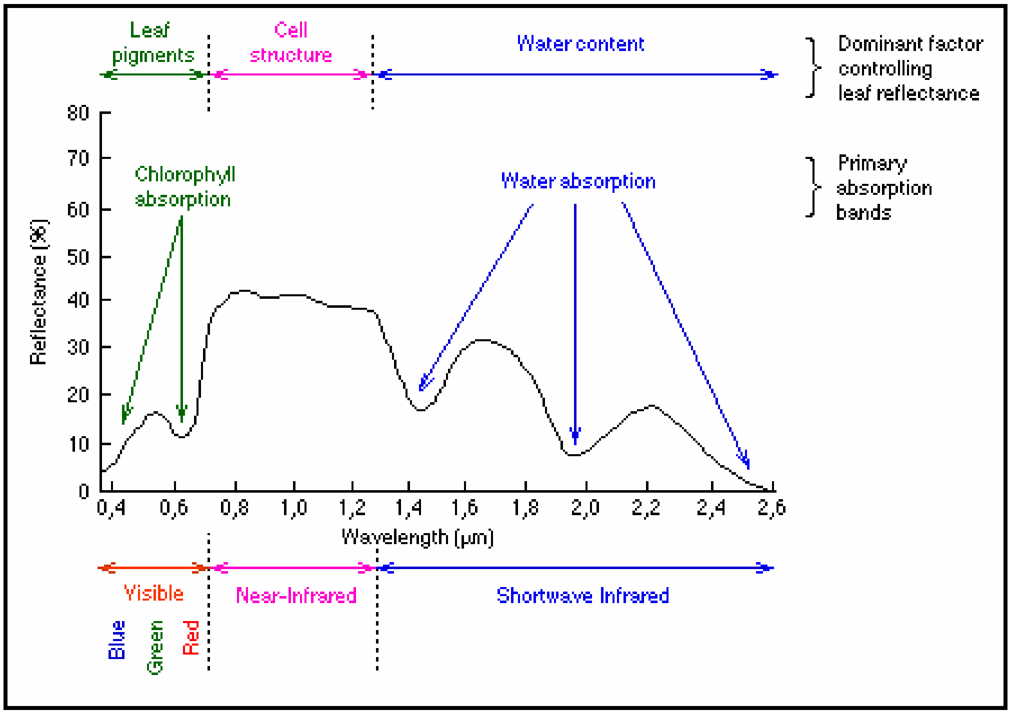


Figure 2.13: Spectral response characteristics of green vegetation. Chlorophyll contained in a leaf has strong absorption at 450 nm and 670 nm and high reflectance in the near-infrared (700–1,200 nm). In the shortwave-IR, vegetation displays three absorption features that can be related directly to the absorption spectrum of water (blue line) contained within the leaf (***Hoffer, 1978***)

The remote sensing of vegetation also benefits from the fact that the wavelengths of visible light to which chlorophyll is sensitive occupy an atmospheric 'window', i.e. the light passes relatively unhindered through the atmosphere to the Earth's surface. Even if positioned outside the Earth's atmosphere, any remote sensing system that is tuned to image these wavelengths will enjoy a relatively high signal, and this is the reason that so many sensing systems utilize the visible spectrum. More than 45 per cent of the radiant energy down welling on the Earth's surface during the day is in the visible wavelength region, and it is also no coincidence that this is the portion of the spectrum that plants have evolved to initiate photosynthetic reactions (***Purkis and Klemas, 2011***).

All photosynthetic organisms have one or more pigments capable of absorbing visible radiation. Two portions of the electromagnetic spectrum are strongly absorbed by the chlorophyll pigment. These correspond to blue (450 nm) and red light (670 nm), and the magnitude of the absorption is directly related to the amount of radiant energy utilized by the plant. The upshot is a small peak at 500–600 nm (visible green), which explains why our eyes perceive most vegetation to be green. As shown by Figure 5.1, the near-infrared region (700–1,200 nm) acts inversely, displaying a pronounced peak in reflectance. It is a fairly unique characteristic of green vegetation that the reflectance in the near-IR is several times as large as that in the visible band. Since the transition from low reflectance in the red to high in the near-infrared is very abrupt, it is often termed the 'red edge'. The red edge position (REP) shifts according to changes of chlorophyll content, leaf area index (LAI), biomass and hydric status, age, plant health levels and seasonal patterns. For healthy plants with high chlorophyll content and high LAI, the red edge position shifts toward the longer wave lengths; when a plant suffers from disease or chlorosis and low LAI, it shifts toward the shorter wavelengths (**Figure 2.14**). Many techniques have been developed to study quantitatively and qualitatively the status of vegetation from satellite images. The vegetation index concept was developed as a method of reducing the number of variables present in multi-spectral measurements down to one unique parameter. Vegetation indices are combinations of spectral channels, blended in such a way that they strengthen the spectral contribution of green vegetation. This is achieved by minimizing the disturbing influences of soil background, irradiance, solar position, yellow vegetation and atmospheric attenuation variations (***Purkis and Klemas, 2011***).

Climate change will cause shifts in areas suitable for cultivation of a wide range of crops. It could be used current and projected future climate data for ~2055, and the different models to predict the impact of climate change on different areas. Most detrimentally affected in terms of reduction of suitable areas for a range of crops will be sub-Saharan Africa and the Caribbean, areas with the least capacity to cope. Conversely, Europe and North America will see an increase in area suitable for cultivation. These regions have the greatest capacity to manage climate change impacts. Altered and unpredictable weather patterns can increase crop vulnerability to pests, diseases and the effects of extreme climate events such as high temperatures, droughts and torrential rains. Sequential extremes, such as droughts followed by intense flooding rains, are catastrophic in themselves and are compounded by ecological effects such as the expansion of the ranges of pathogens, diseases, and pests that affect human populations and agricultural production (***Rosenzweig et al. 2001***).

The impact of climate change on production of various crops varies markedly depending mainly on the region, growing season, the crops and their temperature thresholds. Cereals, oilseed and protein crops depend on temperature and, in many cases, day length, to reach maturity. Temperature increase may shorten the length of the growing period for these crops and, in the absence of compensatory management responses, reduce yields and change the area of cultivation by rendering unsuitable some currently cultivated areas and suitable, others not currently cultivated (***Lane and Jarvis, 2007***).

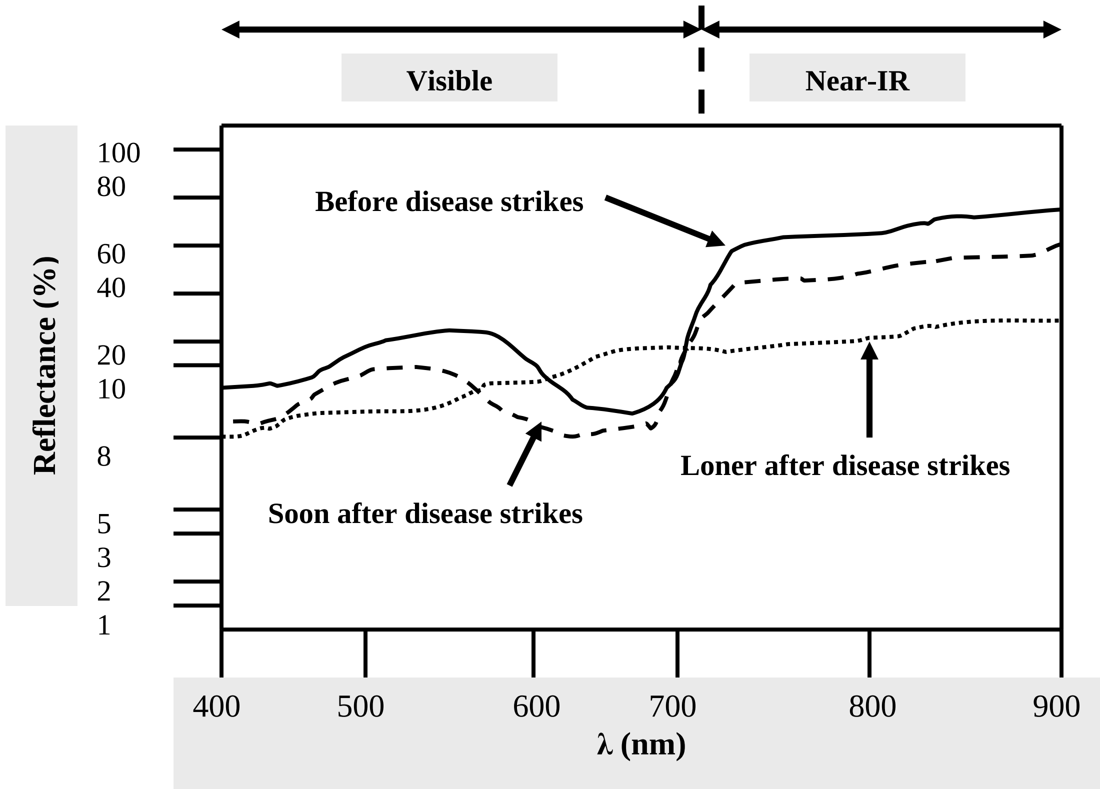


Figure 2.14: Spectral reflectance changes in some plants impacted by diseases, drought, pollution or insect infestations (adapted from ***Purkis and Klemas, 2011***)

The challenges that climate change presents to humanity require an unprecedented ability to predict the responses of crops to environment and management. GIS and crop simulation models are two powerful and highly complementary tools that are increasingly used for such predictive analyses. The role of both technologies in predicting future situations centres around extrapolation. For GIS, extrapolation from the past based on correlation in a very loose sense plays an important role.

The inherently spatial aspects of climate and climate change make them readily amenable for incorporation into a GIS-based analysis system. It is becoming ever more apparent that climatic changes are occurring non-uniformly across regions or agroecosystems. GIS provides a useful tool to capture this spatial heterogeneity and provides powerful ways in which to visualize and communicate the actual or potential changes that are occurring. A GIS-based framework has been the fundamental element of several major assessments of the potential impact of climate change on agriculture (***Hodson and White, 2010***).

The flexibility of GIS-based analysis systems to handle differing scenarios in a rapid and efficient manner is another important factor. The suite of advanced global general circulation models (GCMs) that inform major assessments such as those of the IPCC (***e.g., Solomon et al. 2007***), and the accompanying emission scenarios developed for the IPCC assessments (***IPCC, 2000***) form the basis of many climate change assessments. Increasingly, the outputs of the GCMs under differing emissions scenarios are available in data formats suitable for direct use in GIS-based systems. The availability of multiple GCM outputs, coupled to GIS-based systems, has permitted increasing opportunities for analysis of spatial convergence or divergence of GCM outputs at global or regional scales (***Lobell et al. 2008***).

Common tasks within a GIS include the input, storage, manipulation, analysis and display (often in the form of maps or graphs) of georeferenced data. Mapping is a key output of any GIS, but it is certainly not the only functionality. Common data inputs include data in either vector or raster (gridded) formats. The latter are particularly useful for the representation of continuous data (e.g. climatic variables) and cell-by-cell modelling.

Globally, GIS is applied to disciplines ranging from managing utility networks to health, archaeology and ecology. Increasingly, it is a common component of climate change assessments. The geographic aspect of GIS makes it an interesting option for application to agricultural problems and priority setting because so many of the environmental and socio-economic factors that impact agriculture or agricultural research vary greatly over regions. Typical examples would include rainfall patterns, soil variability, disease and pest distribution, market locations, crop distributions, land-use patterns and human demographics (**Table 2.19**). **Hodson and White** (**2010**) reported about the different uses for GIS as follows:

- GIS has seen widespread use for delineation of suitability zones and agroecological zonation. The ability to combine multi-thematic data based on common geography has been an extremely powerful tool. Common approaches to general crop suitability mapping have included the geographical overlay and intersection of key factors such as optimal temperature and moisture ranges, soil types and topographic features. GIS is perfectly suited for undertaking such analysis.
- Similar approaches have been undertaken to determine environmental niches in which wild relatives of crops are most likely to occur.
- Location-based climatic factors have also formed the basis of zonations for targeting germplasm of major food crops.
- Climate-based mapping of potential pest and disease probability occurrence zones is also relevant to the scope of this review. This has been undertaken using very similar approaches to those described for wild relatives and crops.

- Abiotic stresses, such as drought, have also been assessed using GIS-based analytical approaches. Again climate is a key driver and GIS captures the spatial variation that is essential to interpretation in an agricultural context.

Table 2.19: Examples of typical application themes for GIS/spatial technologies (cited from ***Hodson and White, 2010***)

Thematic area	Comment	Example reference
Rainfall/climate patterns	Interpolated raster (gridded) surfaces derived from meteorological station data	Hijmans *et al.* (2005)
Soil variability	Spatial variation of major soil types and derived soil properties	Batjes (2009)
Disease and pest distribution	Actual distributions and climatic suitability zones	Sutherst and Maywald (2005)
Market locations/accessibility	Accessibility surfaces based on least cost distance travel times	Uchida and Nelson (2009)
Crop distributions y	Spatial allocation of reported agricultural census data into most likely areas using land use and suitability	You *et al*. (2009)
Land-use patterns	Satellite-derived land-cover estimates on varying spatial and temporal scales	Bicheron *et al*. (2006)
Human demographics	Gridded surfaces of human population density	CIESIN, Columbia University and CIAT (2005)
Abiotic stresses	Modelled spatial distributions of key stresses, e.g. drought, heat	Hodson and White (2007)
Identification of wild species collection sites/suitability zones	Actual distributions and modeled ecological niches for important wild relatives of crop species	Jarvis *et al*. (2003)
Crop suitability zones and agroecological zonation	Climate, soil and landform-based agroecological zones for major crops	Setimela *et al*. (2005)

These examples illustrate how GIS has been the key technology applied to a range of differing agroecological themes. Spatial integration of multi-thematic data sets was a common element, but so too was use of climate data. This pivotal role of GIS in agroclimatic analysis is relevant whether the analysis is based on current or historical climate data or predicted future climate data. The increasing availability of outputs from a range of GCMs under varying emission scenarios is permitting a range of GIS-based assessments of the potential characteristics of future crop production zones, and associated abiotic and biotic stresses. Several illustrative case studies will be described in succeeding sections that build upon the examples and themes already outlined.

The application of GIS-based systems to agroclimatic analysis under current climate conditions has already been outlined. The availability of a range of GCM outputs run under a suite of emission scenarios is now permitting similar approaches for potential future climates. With any such approaches it should always be borne in mind that outputs from the GCMs are not precise and variation occurs between different models and scenarios. In addition, for agricultural assessments downscaled GCM results are usually required and this introduces another set of uncertainty. Despite these caveats, the results of such studies can provide useful indications of the potential magnitude of change and the spatial variation that may occur. Selected examples are given below in order to illustrate the range of approaches being undertaken (***Hodson and White, 2010***).

Most vegetation indices utilize the red and near-infrared bands. For example, based on the reflectance difference that green vegetation displays between the visible region (10 percent) and the near-infrared region (50 per cent) of the electromagnetic spectrum (e.g. in channels 1 and 2 of the AVHRR images of the NOAA satellites), the Normalized Difference Vegetation Index (NDVI) can be expressed as:

$$NDVI = (NIR - R)/(NIR + R)$$

Where: R is the red band and NIR is the near-infrared band reflectance. The range of values obtained by the NDVI is between −1 and +1. Only the positive values correspond with the vegetated zones, and the higher the index, the greater the chlorophyll content of the target. Negative values, generated by a higher reflectance in the visible region than in the infrared region, are due to clouds, snow, bare soil and rock. The value of the NDVI can change depending on the land use, the season, the hydric situation and the climate of the area (**Figure 2.15**) (***US Geological Survey, 1997***).

To quantify pigments in vegetation, hyper-spectral data with high radiometric and spatial resolution are required. To this end, airborne instruments such as the AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) and HyMap have been used, as well as more recent experimental space borne imaging spectrometers such as the Compact High Resolution Imaging Spectrometer (CHRIS) and Hyperion. Before performing image analysis for thematic land cover or vegetation mapping, one must choose or develop a classification system which meets the needs of the problem to be addressed. A workable classification system must meet at least the following criteria, i.e. it must be:

- Exhaustive, i.e. all possible land covers or conditions must be assigned to a class;
- Mutually exclusive, i.e. any land cover must be assignable to one and only one class;
- Hierarchical, i.e. begin at a general level and divide each class into subclasses at the next lower level;
- Flexible, i.e. allow the production of many different specialty maps (e.g. data layers of a GIS) and be able to respond to changing needs ***(Jensen, 2007)***.

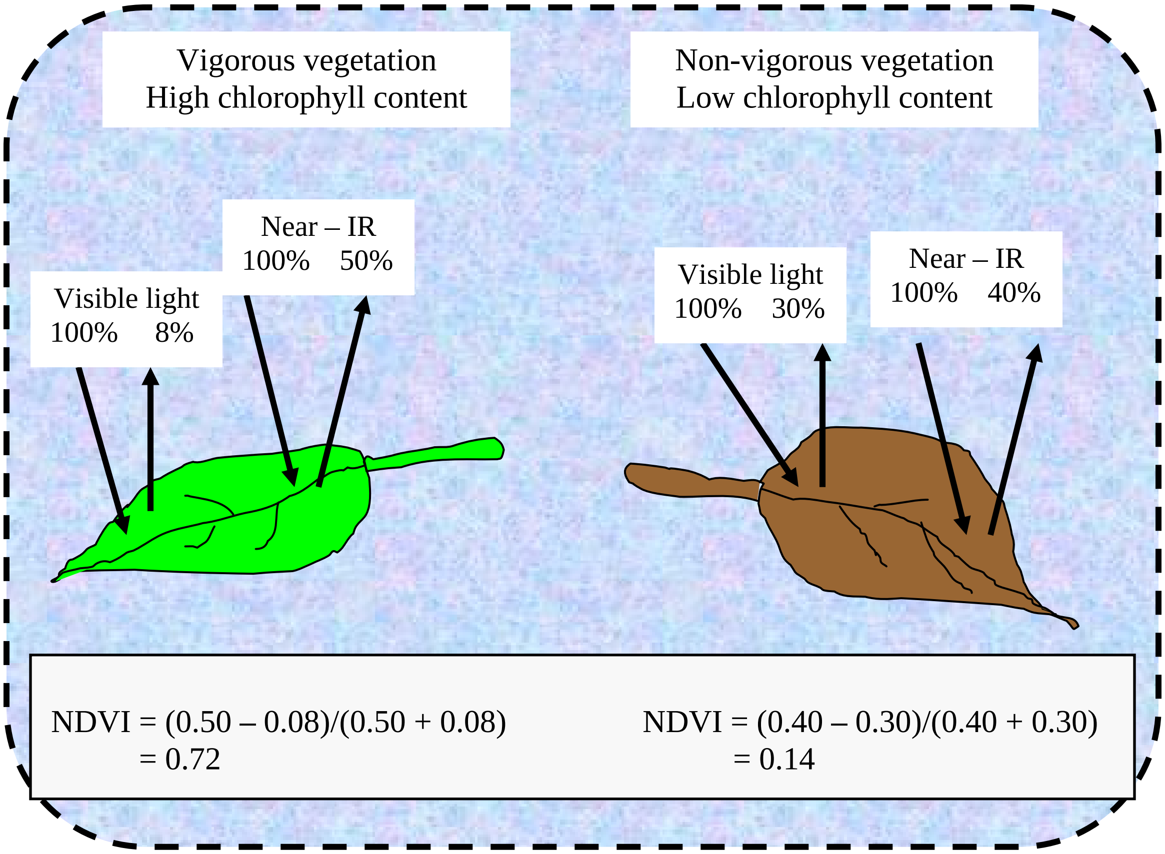


Figure 2.15: The NDVI algorithm capitalizes on the fact that green vegetation reflects less visible light and more near-IR, whereas sparse or less green vegetation reflects a greater portion of the visible and less near-IR. By combining these reflectance characteristics in a ratio, NDVI provides a useful index of photosynthetic activity (adapted from ***Purkis and Klemas, 2011***)

2.3.3 *Hyperspectral Remote Sensing of Vegetation Bioparameters*

The term “multi” is derived from the Latin word for “many” and “hyper” is the Greek word for “over,” “above,” or an “exaggerated amount.” These, combined with “spectral,” which relates to colors, are combined to form “multispectral” and “hyperspectral,” which figuratively mean “many colors.” The science of multispectral and hyperspectral remote sensing is based on taking a portion of the electromagnetic spectrum and breaking it into pieces for the purpose of analytical computations (***Borengasser et al. 2008***).

Imaging spectroscopy, as a new remote-sensing technique (i.e., “*hyperspectral remote sensing*”), is of growing interest to Earth remote sensing. Hyperspectral remote sensing refers to a special type of imaging technology that collects image data in many narrow contiguous spectral bands (< 10-nm bandwidth) throughout the visible and solar-reflected infrared portions of the spectrum. Since many Earth surface materials show diagnostic absorption features that are from 20- to 40-nm spectral resolution, spectral imaging systems, which acquire spectral data in contiguous narrow bands at <10-nm resolution, can produce data with sufficient resolution for direct identification of those materials with diagnostic spectral features. However, traditional remote sensing systems, which usually are called "multi-spectral remote sensing" systems and acquire data in a few discrete wide bands (usually >50-nm bandwidth), cannot resolve these spectral features. Therefore, the value of hyperspectral remote sensing lies in its ability to acquire a complete reflectance spectrum for each pixel in an image, and it is developed for improving identification of materials and quantitative determination of physical and chemical properties of targets of interest, such as minerals, water, vegetation, soils, and human-made materials (***Pu and Gong, 2011***).

Imaging spectroscopy was developed for mineral mapping in the early 1980s. The first imaging spectrometer, named the Airborne Imaging Spectrometer (**AIS**), was developed by the Jet Propulsion Laboratory (**JPL**) with a total of 128 spectral bands covering the spectral range between 0.9 and 2.4 μm in late 1982. Ecology and the study of terrestrial vegetation are important application fields for hyperspectral remote sensing. A number of forest ecosystem variables, including leaf area index (**LAI**), absorbed fraction of photosynthetically active radiation (**fPAR**), canopy temperature, and community type are correlated with remotely sensed data or their derivatives. However, sensors in common use, such as the Landsat Multispectral Scanner (**MSS**) and the Thematic Mapper (**TM**), which integrate radiance data over wide bands of the electromagnetic spectrum, have limited value in studying the dominant canopy reflectance features such as the red spectral absorption band, near-infrared (**NIR**) reflectance band, and mid-infrared water absorption band. Moreover, the extraction of red edge and other optical parameters (***Pu et al. 2004***) that are related to plant stress or senescence is impossible with broadband sensors. Many minerals found on the Earth's surface have unique and diagnostic spectral reflectance signatures. Plants, on the other hand, are composed of the same few compounds and therefore should have similar spectral signatures. Indeed, major features of "peaks and valleys" along the spectral reflectance curve of a plant are due to the presence of pigments (e.g., chlorophyll, Chl.), water, and other chemical constituents. Therefore, characterization of diagnostic absorption features in plant spectra with hyperspectral data as done in geological mapping and mineral identification can also be done for extraction of the biochemical and biophysical parameters of plants (***Asner and Martin, 2008***). Electromagnetic spectrum: each photon of the electromagnetic spectrum has a wavelength determined by its energy level. Light and other forms of electromagnetic radiation commonly are described in terms of their wavelengths. The visible spectrum is shown in **Figure 2.16**. Its relationship to the entire electromagnetic spectrum is detailed in **Figure 2.17 and Table 2.20** (***Borengasser et al. 2008***).

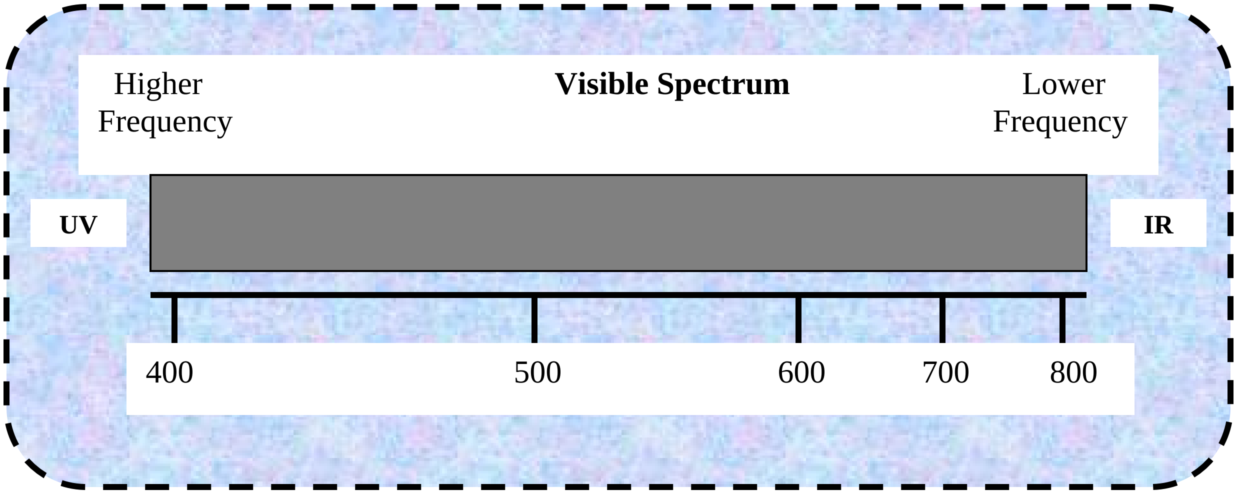


Figure 2.16: Visible spectrum with wavelengths in nanometers (adapted from ***Borengasser et al. 2008***)

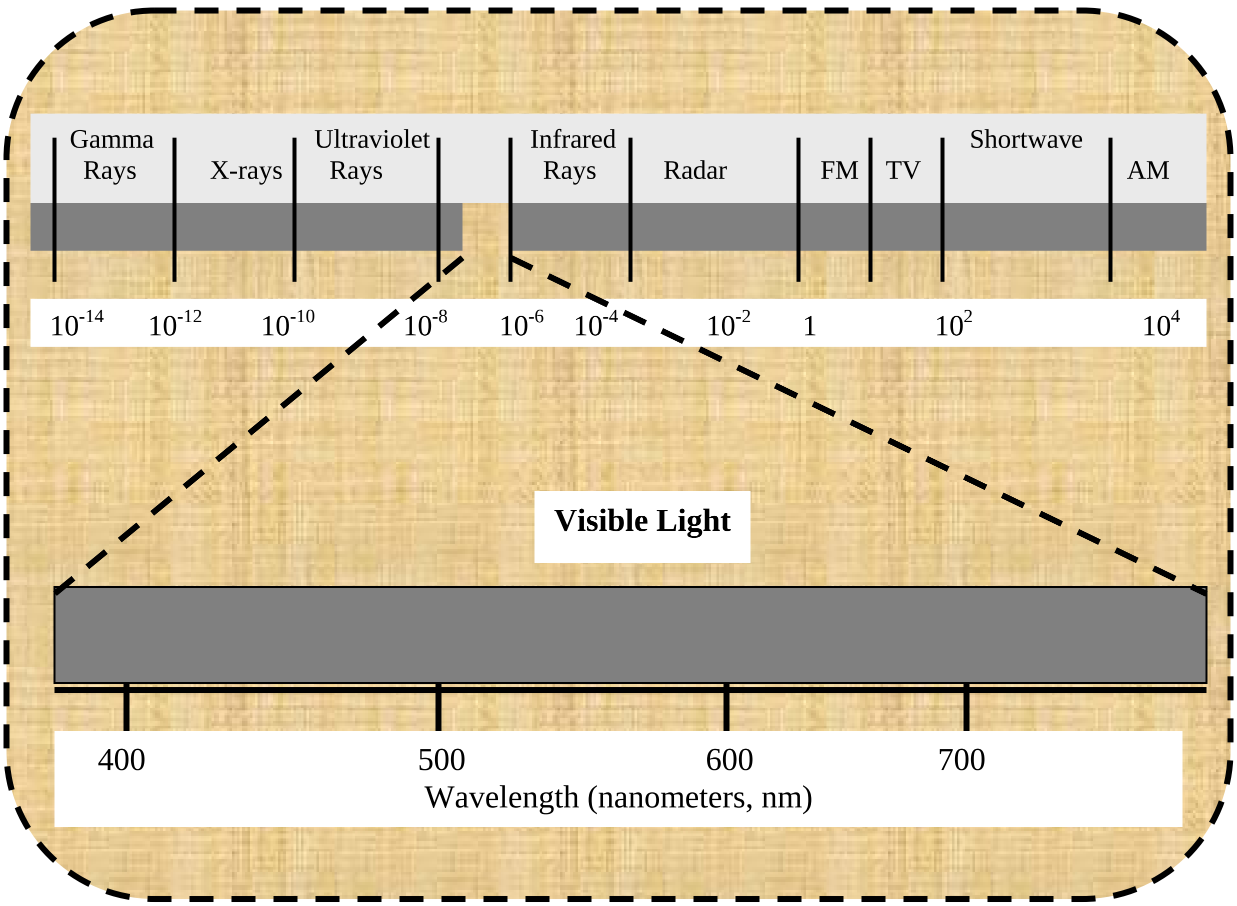


Figure 2.17: Electromagnetic spectrum (***Borengasser et al. 2008***)

Table 2.20: Principal divisions of the electromagnetic spectrum (adapted from ***Campbell and Wynne 2011)***

Division	Limits
Gamma rays	< 0.03 nm
X-rays	0.03–300 nm
Ultraviolet radiation	0.30–0.38 μm
Visible light	0.38–0.72 μm
Infrared radiation	
Near infrared	0.72–1.30 μm
Mid infrared	1.30–3.00 μm
Far infrared	7.0–1,000 μm (1 mm)
Microwave radiation	1 mm–30 cm
Radio	≥ 30 cm

Hyperspectral sensors aboard different types of platforms have made it possible to acquire higher spectral resolution data that contain more information on the subtle spectral features of plant canopies. The use of narrow (1–10 nm) instead of broad (50–200 nm) spectral bands could offer new potentials for remote sensing applied to vegetation. Hyperspectral data have been proven to be more useful in estimating biochemical content and concentration at both the leaf and canopy levels and some other ecosystem components such as LAI, plant species composition, and biomass than traditional remotely sensed data. Therefore, besides classification and identification of vegetation types, in terrestrial ecosystem study, hyperspectral remote sensing can be applied to the estimation of biochemical and biophysical parameters and to the evaluation of ecosystem functions (***le Maire et al. 2008***).

Any hyperspectral data collected from an airborne or space borne platform is influenced by the atmospheric conditions at the time the data is collected. If the weather is sunny and clear, the data will be optimum. Data collected when the atmosphere is cloudy or humid, however, will be affected by those conditions. Therefore, knowing the principles of spectral radiometry and understanding how to use its concepts is important when interpreting the data collected by hyperspectral sensors. Radiometry is the physical measurement of electromagnetic radiation within the ultraviolet, visible, and infrared wavelengths. A radiometer is a device used to measure the radiant flux or power in electromagnetic radiation. The most important characteristics of a radiometer are spectral range (wavelengths measured), spectral sensitivity (sensitivity vs. wavelengths measured), field of view (18 degrees or limited to a certain narrow field), and directional response (typically the cosine response of the unidirectional response) (***Borengasser et al. 2008***).

Radiometers can use all kinds of detectors. For example, thermal detectors absorb energy and convert it to a signal. Photon (photodiode) detectors have a constant response per quantum (light particle). The radiation detector within a radiometer is usually a bolometer, which absorbs the radiation falling on it and, as a result, rises in temperature. This rise can then be measured by a thermometer. This temperature rise can be related to the power in the incident radiation. To understand hyperspectral imaging, first you need to understand its sensors and how they collect data, the number of bands and bandwidth, the type of platform from which the data is gathered, and the resolution of the data. In general, sensors gather data either passively or actively. Passive sensors collect and record electromagnetic energy that is reflected or emitted by surface features, typically through an optical lens. Examples include film or digital cameras and thermal infrared sensors, which detect emitted heat energy. Active sensors generate their own energy and then collect the signal that is reflected from the surface of the Earth. Examples of active sensors include RADAR (Radio Detection and Ranging) and LIDAR (Light Detection and Ranging) (***Borengasser et al. 2008***).

For hyperspectral imagery, the data source includes ten or more bands of data. The bandwidth of the data typically ranges from 1 to 15 nanometers (a nanometeris one-billionth of a meter). In contrast, multispectral data typically consist of 3 to 7 bands of data with bandwidths ranging from 50 to 120 nanometers. The platform from which the data is collected is either spaceborne or airborne. Spaceborne refers to satellite sensors, such as Landsat, Ikonos, QuickBird, ASTER (Advanced Spaceborne Thermal Emission and ReflectionRadiometer), or Hyperion. Hyperion is a hyperspectral spaceborne sensor (using the strict definition of hyperspectral—number of bands and bandwidth). Airborne refers to fixed wing (airplane) or rotary (helicopter) platforms. Examples of airborne hyperspectral sensors include AISA, AVIRIS (Airborne Visual and Infra-Red Imaging Spectrometer), CASI, and HyMap (**Table 2.21**; ***Borengasser et al. 2008***).

Spectral Characterization of Typical Bioparameters

Farmers can order spectral imagery of their fields to determine the status of their land and whatever is growing on it. For example, spectral imagery can indicate the amount of fertilization required in specific locations that are designated with GPS coordinates. Agricultural machinery on the market today has the capability to load this information into computers built into the machinery and automatically adjust the amount of fertilizer deposited based on the information contained in the spectral imagery (***Borengasser et al. 2008***).

The spectral reflectance properties and characteristics of a list of typical plant bio parameters, including the biophysical and biochemical parameters (**Table 5.1**), have been the subject of systematic plant spectral reflectance studies. Typical biophysical parameters for their spectral analysis consist of vegetation canopy **LAI**, specific leaf area (**SLA**), crown closure (**CC**), vegetation species and composition, biomass, effective absorbed fPAR, and net primary productivity (**NPP**), which reflect photosynthesis rate. Typical biochemical parameters are major pigments (**Chls**, carotenoids [**Cars**], and anthocyanins [**Anths**]), nutrients (nitrogen [N], phosphorus [P], and potassium [K]), leaf or canopy water content (W), and other biochemicals (e.g., lignin, cellulose, and protein). Analysis results are useful for determining the physicochemical properties of plants derived from spectral data and helpful for extracting bioparameters in order to assess vegetation and ecosystem conditions. Some analysis results of spectral characteristics for the list of typical biophysical and biochemical parameters from hyperspectral data are summarized in the following topics:

(1) ***Leaf Area Index, Specific Leaf Area, and Crown Closure***

The LAI, SLA, and CC are important structural parameters for quantifying the energy and mass exchange characteristics of terrestrial ecosystems such as photosynthesis, respiration, transpiration, the carbon and nutrient cycle, and rainfall interception. The LAI parameter quantifies the amount of live green leaf material present in the canopy per unit ground area, whereas SLA describes the amount of leaf dry mass present in the plant canopy. The CC parameter can only quantify the percentage of area covered by the vertical projection of live green leaf material present in the canopy. The physiological and structural characteristics of plant leave determine their typically low visible-light reflectance, except in green light (***Borengasser et al. 2008***).

The high NIR reflectance of vegetation allows optical remote sensing to capture detailed information about the live, photosynthetically active forest canopy structure, and thus help understand the mass exchange between the atmosphere and the plant ecosystem (***Zheng and Moskal 2009***). As LAI and CC increase, many absorption features become significant due to changes in their amplitude, width, or location. The absorption features, including those caused by pigments in the visible region and by water content and other biochemicals in the shortwave infrared (SWIR) region, are useful in extracting and mapping LAI and CC. Different from LAI and CC, the spectral properties of SLA are not directly related to water absorption bands in the full range of a vegetation spectrum. However, SLA has a leaf structural property linked to the entire constellation of foliar chemicals and photosynthetic processes. It is related to the NIR spectral reflectance that is dominated by the amount of leaf water content and leaf thickness. Thus, at the leaf level, SLA is highly correlated with leaf spectral reflectance. Optical remote sensing, especially hyperspectral remote sensing, is aimed at retrieving the spectral characteristics of leaves, quantified by LAI, SLA, and CC, which are determined by the internal biochemical structure and pigments content of leaves. Currently, many spectral analysis techniques and methods are available for extracting and assessing the biophysical parameters LAI, SLA, and CC from various hyperspectral sensors, especially imaging spectrometers, such as spectral derivatives, spectral position variables, spectral indices, and physically based models (***Asner and Martin, 2008***).

(2) *Biomass*

Leaf canopy biomass is calculated as the product of the leaf dry mass per area (LMA; unit: g m^{-2}, or the inverse of SLA) and LAI. Therefore, based on the spectral responses to LAI and LMA, both biophysical parameters can be estimated from hyperspectral data; thus, the leaf mass of the entire canopy is estimated. Many VIs, such as the normalized difference VI (NDVI) and the SR constructed with NIR and red bands have been developed and directly applied to estimate leaf or canopy biomass. It has been recommended that VIs remove variability caused by canopy geometry, soil background, sun view angles, and atmospheric conditions when measuring biophysical properties. Broadband VIs use, in principle, average spectral information over a wide range, resulting in the loss of critical spectral information available in specific narrow (hyperspectral) bands. Since many narrow bands are available for constructing VIs, selection of the correct wavelengths and bandwidths is important. When some VIs derived from hyperspectral data are used to estimate some biophysical parameters, narrow bands (10 nm) perform better than broadband (e.g., TM bands) using standard red/NIR and green/NIR NDVIs (NDVIgreen). For example, NDVISWIR constructed with reflectances at wavelengths 1540 and 2160 nm is the best index for leaf mass estimation (***le Maire et al. 2008***); many hyperspectral bands in the SWIR region and some in the NIR region have the greatest potential to form spectral indices for LAI estimation (e.g., most effective band wavelengths centered around 820, 1040, 1200, 1250, 1650, 2100, and 2260 nm with bandwidths ranging from 10 to 300 nm; ***Gong et al. 2003***).

(3) *Species and Composition*

Foliage spectral variability among individual species, or even within a single crown, is attributed not only to differences in internal leaf structure and biochemicals (e.g., water, Chl content, epiphyll cover, and herbivory) but also to difference and variation in the phenology/physiology of plant species. In addition, the relative importance of these biochemical and structural properties among individual species is also dependent on measured wavelength, pixel size, and ecosystem type. Few studies have been systematically carried out to determine the best wavelengths suitable for species recognition in the field. This obviously depends on species-specific biochemical characteristics that are related to foliar chemistry (***Borengasser et al. 2008***).

Although either of the two by itself is insufficient to identify species, combined information can differentiate between species. For example, red pine and hemlock were reported to have very similar N concentration, but very different levels of lignin. **Pu (2009)** used 30 selected spectral variables evaluated by analysis of variance (ANOVA) from in situ hyperspectral data to identify 11 broadleaf species in an urban environment. Among the 30 selected spectral variables, most of the spectral variables are directly related to leaf chemistry. For example, some selected spectral variables are related to water absorption bands around 0.97, 1.20, and 1.75 μm, and the others are related to spectral absorption features of Chls, red-edge optical parameters, simple ratio (SR), vegetation index (VI), and reflectance at 680 nm, and other biochemicals such as lignin (near 1.20 and 1.42 μm), cellulose (near 1.20 and 1.49 μm), and N (near 1.51 and 2.18 μm). In identifying invasive species in Hawaiian forests from native and other introduced species by remote sensing, **Asner et al. (2008)** confirmed the viewpoint that the observed differences in canopy spectral signatures are linked to relative differences in measured leaf pigments (Chls and Cars), nutrients (N and P), and structural (SLA) properties, as well as to canopy LAI.

(4) ***Pigments: Chlorophylls, Carotenoids, and Anthocyanins***

The Chls (Chl-a and Chl-b) are Earth's most important organic molecules, as they are the most important pigments necessary for photosynthesis. The second major group of plant pigments, composed of carotene and xanthophylls, is Cars, whereas Anths are water soluble flavonoids, which form the third major group of pigments in leaves, but there is no unified explanation for their presence and function. Published spectral absorption wavelengths of isolated pigments show that Chl-a absorption features are around 430 and 660 nm and Chl-b absorption features are around 450 and 650 nm *in vivo*. But it is known that in situ Chl-a absorbs at both 450 and 670 nm. Cars absorption feature in the blue region is at 445 nm in vivo and β-carotene at 470 nm *in vivo*. But it is also known that *in situ* Cars absorb at 500 nm and even at wavelengths that are a little bit longer. The absorption feature of Anths in the green region is at 530 nm in vivo, but *in situ* Anths absorb around 550 nm. Based on the spectral properties of the pigments, some researchers have used red edge optical parameters to estimate plant leaf and canopy Chls content and concentration. However, most of them have developed and used various VIs, constructed in either ratios or normalized difference ratios of two narrow bands in the visible and NIR regions, to estimate the major plant pigments Chls, Cars, and Anths at leaf or canopy levels (***Rama Rao et al. 2008***). In addition, many researchers also employ physically based models at leaf or canopy levels to retrieve the pigments and use data transform approaches like wavelet analysis to retrieve Chl concentration from leaf reflectance spectra (***Blackburn and Ferwerda, 2008***).

The traditional method of assessing the health of a tree, a visual inspection, is subjective and does not directly measure tree vigor. In contrast, a nonvisual method that allows tracking of pigment concentrations (e.g., chlorophyll) could provide an objective, early warning indicator of stand condition. Early detection could help to identify stands requiring remedial or salvage action before damage is visible and potentially before biomass loss occurs. Optical indices derived from the red edge (the region of rapid transition between red and near infrared reflectance) are especially useful because they are sensitive to both chlorophyll content (chla+b) and canopy structure. Several investigators have related changes in chla+b to a shift in position of the spectral red edge. This shift has been associated with plant stress, forest decline, and leaf development (***Borengasser et al. 2008***).

(5) ***Nutrients: Nitrogen, Phosphorous, and Potassium***

The foliage and canopy N is related to a variety of ecological and biochemical processes (***Martin et al. 2008***). It is the most important nutrient element needed by plants for growth. The second and third most limiting nutrient constituents, P and K, are essential in all phases of plant growth; they are used in cell division, fat formation, energy transfer, seed germination, and flowering and fruiting. Among the three basic nutrient elements, N has significant absorption features that have been found in the visible, NIR, and SWIR regions. According to **Curran (1989)**, N absorption features in their isolated form are located around 1.51, 2.06, 2.18, 2.30, and 2.35 μm. Since many biochemical compounds comprise N, such as Chls and protein, their spectral properties are also characterized by N concentration in plant leaves. It seems that P has no direct and significant absorption features across the visible, NIR, and SWIR regions, but it does indirectly affect the spectral characteristics of other biochemical compounds (***Borengasser et al. 2008***).

The documented spectral changes include a higher reflectance in the green and yellow portions of the electromagnetic spectrum in P-deficient plants and a difference in the position of the long-wavelength edge (the red edge) of Chl absorption band centered around 0.68 μm. Foliar K concentration has only a slight effect on needle morphology, thereby affecting NIR reflectance. This is because the sclerenchyma cell walls are thicker, with a high K concentration, which leads to higher NIR reflectance of leaves. To estimate nutrient concentrations from hyperspectral data, including in situ spectral measurements and imaging data, many analysis techniques and methods have been developed. They include spectral derivatives, spectral indices (***Rama Rao et al. 2008***), spectral position variables, continuum-removal method, statistical regression, and inversion of physically based models (***Cho et al. 2008***).

(6) ***Leaf or Canopy Water Content***

The evaluation of water status in vegetation is an important component of hyperspectral remote sensing. Previous work on assessing the plant water status mainly depended on water spectral absorption features in the 0.40–2.50 μm region. According to **Curran (1989)**, the central wavelengths of the absorption features are around 0.97, 1.20, 1.40, and 1.94 μm. In addition, the reflectance of dry vegetation shows an absorption feature centered at 1.78 μm by other chemicals (cellulose, sugar, and starch) rather than by water, because pure water does not cause such an absorption feature. In general, the reflectance spectra of green and yellow leaves in those absorption bands are quickly saturated and solely dominated by changes in the leaf water content (***Borengasser et al. 2008***).

Table 2.21: Typical plant biophysical and biochemical parameters (adapted from ***Pu and Gong, 2011***)

Biophysical Parameter	**Definition and Description**	**Spectral Response and Characteristics**
LAI	The total one-sided area of all leaves in the canopy per unit area of ground.	The absorption spectral features caused by pigments in the visible region and by water content and other biochemicals in the SWIR region are useful for extracting and mapping LAI and CC.
SLA	Projected leaf area per unit leaf dry mass (cm^2 /g).	Not directly related to water absorption bands, but SLA is a leaf structural property linked to the entire constellation of foliar chemicals and photosynthetic processes.
CC	Percentage of land area covered by the vertical projection of plants (tree crowns).	Same as that for LAI.
Species	Various plant species and species composition.	Spectral differences due to differences and variation in phenology/ physiology, internal leaf structure, biochemicals, and ecosystem type.
Biomass	The total of absolute amount of vegetation present (often considered in terms of the aboveground biomass) per unit area of ground.	Spectral responses to LAI, stand/community structure, species and species composition, and image textural information.
NPP	The net flux of carbon between the atmosphere and terrestrial vegetation can be expressed on an annual basis in terms of net biomass accumulation, or NPP.	Spectra reflect vegetation condition and changes in LAI or canopy light absorption through time in visible and NIR regions.
fPAR	Effective absorbed fPAR in the visible region.	In the visible spectral region 400–700 nm, most absorbed by plant pigments, such as Chl-a and -b, Cars, and Anths; and leaf water and N contents for photosynthesis.
Chls (Chl-a, Chl-b)	Green pigments Chl-a and Chl-b for plant photosynthesis processing, found in green photosynthetic organisms, ($mg\ m^{-2}$ or $nmol\ cm^{-2}$).	Chl-a absorption features are near 430 and 660 nm, and Chl-b absorption features are near 450 and 650 nm *in vivo*. But it is known that in situ Chl-a absorbs at both 450 and 670 nm.
Cars	Any of a class of yellow to red pigments, including carotenes and xanthophylls ($mg\ m^{-2}$).	Cars absorption feature in the blue region is near 445 nm *in vivo*. But it is known that in situ Cars absorb at 500 nm and even at a little bit longer wavelength.
Anths	Any of various water-soluble pigments that impart to flowers and other plant parts colors ranging from violet and blue to most shades of red ($mg\ m^{-2}$).	Anths absorption feature in the green region is at 530 nm in vivo, but in situ Anths absorb around 550 nm (***Gitelson et al. 2009***).
N	Plant nutrient element (%).	The central wavelengths of N absorption features are near 1.51, 2.06, 2.18, 2.30, and 2.35 μm.
P	Plant nutrient element (%).	No direct and significant absorption features

		across 0.40–2.50 μm, but it does indirectly affect the spectral characteristics of other biochemical compounds.
K	Plant nutrient element (%).	Foliar K concentration has only a slight effect on sclerenhyma cell walls, and thus on NIR reflectance.
W	Leaf or canopy water content or concentration (%).	The central wavelengths of those absorption features are near 0.97, 1.20, 1.40, and 1.94 μm.
Lignin	A complex polymer, the chief non-carbohydrate constituent of wood, which binds to cellulose fibers and hardens and strengthens the cell walls of plants (%).	The central wavelengths of lignin absorption features are near 1.12, 1.42, 1.69, and 1.94 μm.
Cellulose	A complex carbohydrate, which is composed of glucose units, and forms the main constituent of the cell wall in most plants (%).	The central wavelengths of cellulose absorption features are near 1.20, 1.49, 1.78, 1.82, 2.27, 2.34, and 2.35 μm.
Protein	Any of a group of complex organic macromolecules that contain carbon, hydrogen, oxygen, N, and usually sulfur, and are composed of one or more chains of amino acids (%).	The central wavelengths of protein absorption features are near 0.91, 1.02, 1.51, 1.98, 2.06, 2.18, 2.24, and 2.30 μm.

2.3.4 *Managing Weather and Climate Risks in Agriculture*

In general, year to year deviations in the weather and occurrence of climatic anomalies/extremes respect of the four seasons are:

i) Cold wave, fog, snow storms and avalanches
ii) Hailstorms, thunderstorms and dust storms
iii) Heat waves
iv) Tropical cyclones and tidal waves
v) Floods, heavy rain and landslides, and
vi) Droughts.

Extreme weather events, and climatic anomalies, have major impacts on agriculture. Of the total annual crop losses in world agriculture, many are due to direct weather and climatic effects such as drought, flash floods, untimely rains, frost hail, and storms. High preparedness, prior knowledge of the timing and management of weather events and climatic anomalies and effective recovery plans will do much to reduce their impact on production levels, on land resources and on other assets such as structures and infrastructure and natural ecosystem that are integral to agricultural operations. Aspects of crop and livestock production, as well as agriculture’s natural resource base, that are influenced be weather and climatic conditions include air and water pollution; soil erosion from wind or water; the incidence and effects of drought; crop growth; animal production; the incidence and extent of pests and diseases; the incidence, frequency, and extent of frost; the dangers of forest and bush fires; losses during storage and transport; and the safety and effectiveness of all on –farm operations (***Mavi and Tupper, 2004***).

Although many ideas are available about ways to adapt to climate variability and change, few of these options have been assessed for their effectiveness under projected future climate conditions and for their potential interactions across sectors and with other stressors. Little attention has been given to the processes that decision makers might use to make appropriate adaptation decisions. In brief, it could be suggested that the adaptation process is fundamentally a risk-management strategy. Managing risk in the context of adapting to climate change involves using the best available social and physical science to understand the likelihood of climate impacts and their associated consequences, then selecting and implementing the response options that seem most effective. Because knowledge about future impacts and the effectiveness of response options will evolve, policy decisions to manage the risk of climate change impacts can be improved if they are done in an iterative fashion by continually monitoring the progress and consequences of actions and modifying management practices based on learning and recognition of changing conditions. Using a risk-management approach, adaptation options for managing the risks associated with climate impacts can then be identified, evaluated, and implemented (***NRC, 2010***; **Figures 2.18, 2.19 and 2.20**).

Adaptation to climate change requires attention now because impacts are already being felt across the world and further impacts are unavoidable, regardless of how immediately and stringently greenhouse gas (GHG) emissions are limited (***IPCC, 2007a***). Adaptation to climate *variability* is nothing new to humanity, but it now seems very likely that climate conditions by the later part of the 21st century will move outside the range of past human experiences (***IPCC, 2007b***). Therefore, historical records and past experience are becoming incomplete guides for the future, and adaptation to climate change needs to become a high national priority. Either we adapt by mobilizing to reduce sensitivities to climate change and to increase coping capacities now, or we will adapt by accepting and living with impacts that are likely in many cases to disrupt our lives and livelihoods. The questions are how, where, and when to adapt—and whether in some cases, if climate change is relatively severe, we may face limits on our ability to avoid painful impacts by adapting. Society and nature have always adjusted to climate *variability* and weather extremes, but climate *change* is moving climate conditions outside the range of past human experiences (***IPCC, 2007b***). While previous experience in coping with climate variability or extremes can provide some valuable lessons for adapting to climate change, there are important differences between coping with variability and planning for climate change. Climate change has the potential to bring about abrupt changes that push the climate system across thresholds, creating novel conditions. Likewise, thresholds in ecosystems and human systems could be crossed, potentially overwhelming their adaptive capacity (***NRC, 2010***).

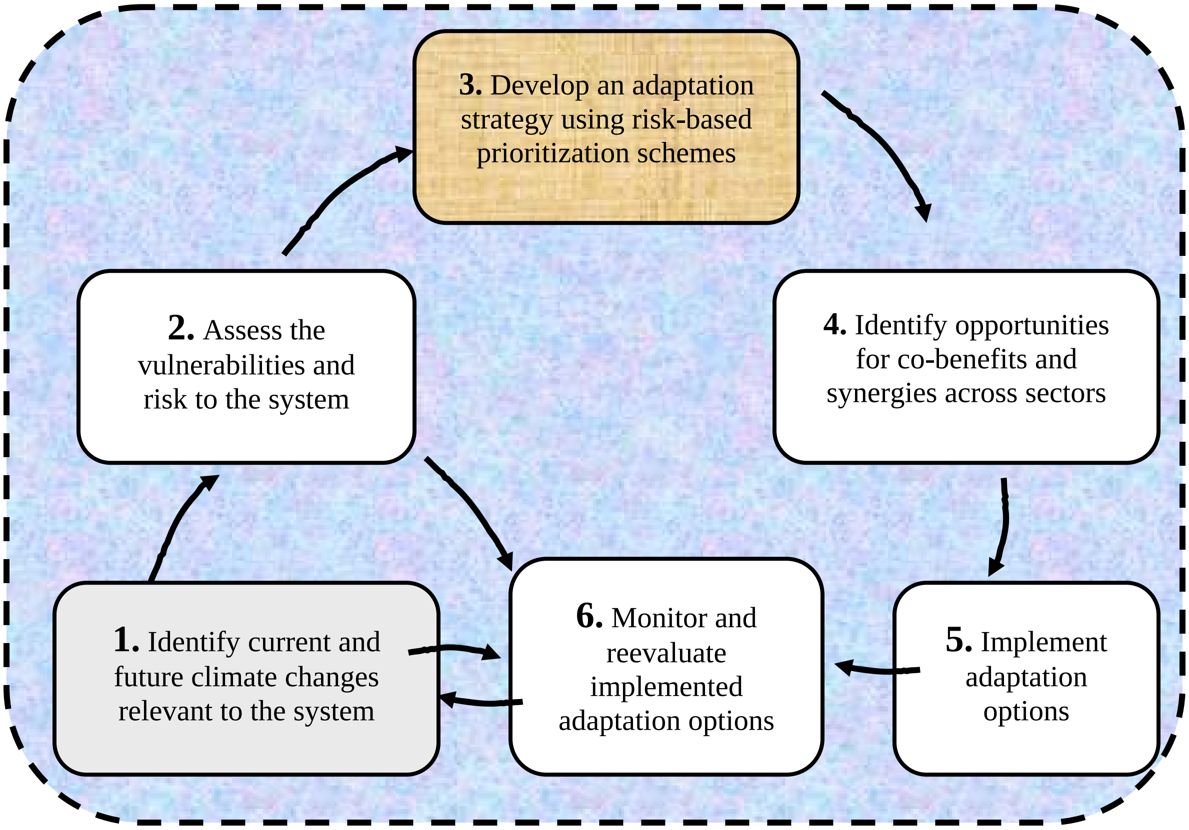


Figure 2.18: The planning process is envisioned to incorporate the following steps: (1) identify current and future climate changes relevant to the system, (2) assess the vulnerabilities and risk to the system, (3) develop an adaptation strategy using risk-based prioritization schemes, (4) identify opportunities for co-benefits and synergies across sectors, (5) implement adaptation options, and (6) monitor and reevaluate implemented adaptation options (adapted from ***NRC, 2010***)

Adaptation is intended to reduce climate change vulnerabilities and impacts. That means any consideration of adaptation planning must begin with consideration of risks associated with climate change vulnerabilities and impacts, to the extent that these can be anticipated. More specifically, adaptation includes (1) the strategies, policies, and measures implemented to avoid, prepare for, and effectively respond to the adverse impacts of climate change on natural and human systems (to the extent that they can be anticipated), and (2) the social, cultural, economic, geographic, ecological, and other factors that determine the vulnerability of places, systems, and populations. Climate-related changes can create new or interact with existing vulnerabilities to cause impacts, including changes in:

- ❖ Temperature, both averages and extremes;
- ❖ Precipitation, both averages and extremes;

- ❖ The intensity, frequency, duration, and/or location of extreme weather events;
- ❖ Sea level; and
- ❖ Atmospheric carbon dioxide (CO_2) concentrations.

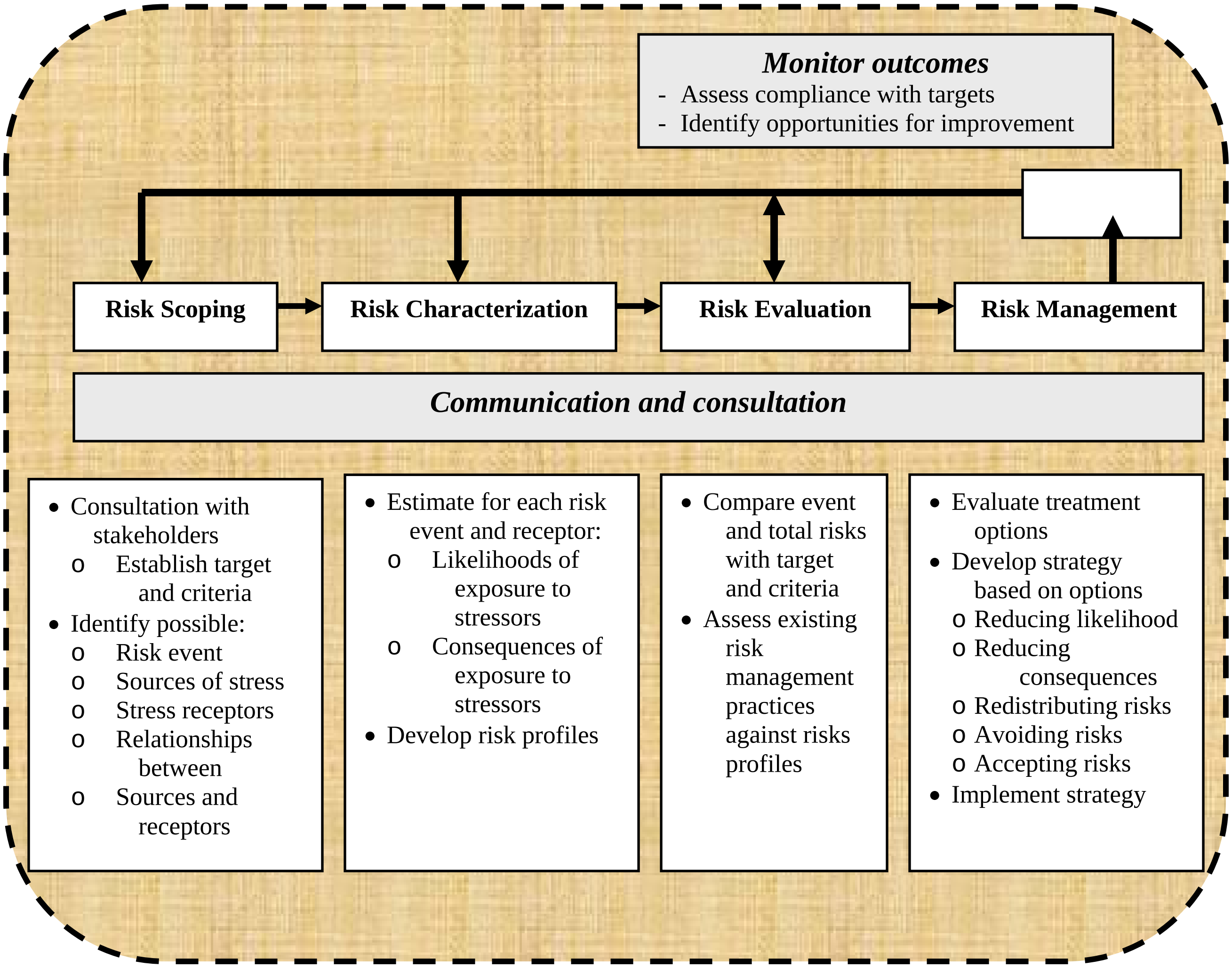


Figure 2.19: Generic methodology for characterizing and managing risks (adapted from ***Silvakumar and Motha, 2007***)

Vulnerability is often defined as the capacity to be harmed. It is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity. Vulnerabilities can be reduced by limiting the magnitude of climate change through actions to limit greenhouse gas (GHG) emissions, reducing sensitivity (the underlying social, cultural, economic, geographic, ecological, and other factors that interact with exposures to determine the magnitude and extent of impacts), or improving coping capacity (the ability to avoid, prepare for, and respond to an impact so that it is not seriously disruptive). Actions to reduce sensitivity and increase coping capacity are keys to effective adaptation to climate change (***NRC, 2010***).

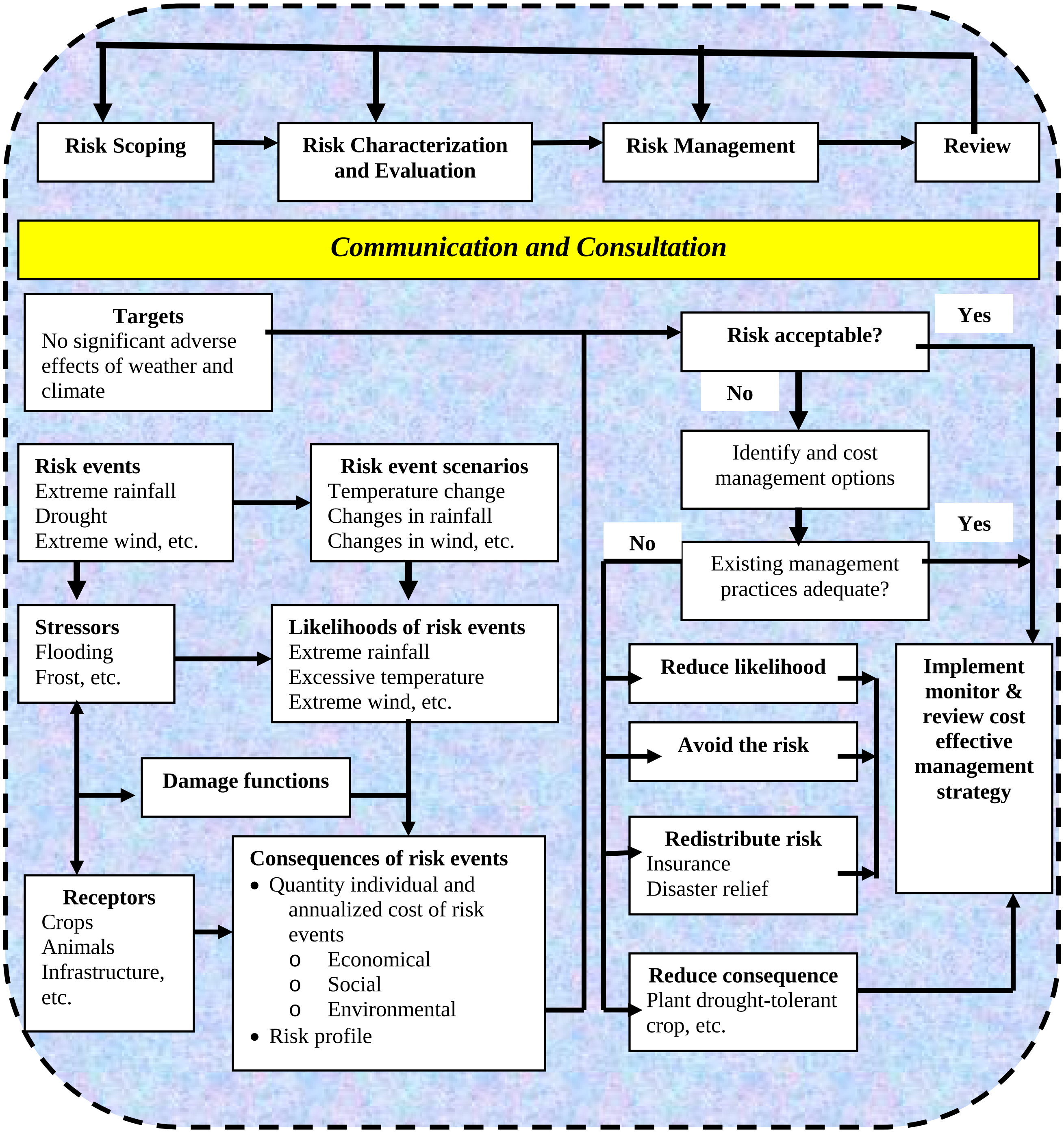


Figure 2.20: Procedures for characterizing and managing risks and their application to the agricultural sector (adapted from ***Silvakumar and Motha, 2007***)

Adaptation is fundamentally a risk-management strategy. Risk is a combination of the magnitude of the potential consequences and the likelihood that they will occur. Managing risk in the context of adapting to climate change involves using the best available social and physical science to understand the likelihood of climate impacts and their associated consequences, then selecting and implementing the response options that seem most effective. Because knowledge about future impacts and the effectiveness of response options will evolve, policy decisions to manage risk can be improved if they incorporate the concept of "adaptive management," which implies monitoring of progress in real time and changing management practices based on learning and as a recognition of changing conditions is incorporated. It is important to be clear at the start about the problem to be managed. Without a shared understanding of the nature of the problem, the desired goals of the stakeholders, and the "decision context", collective risk management is not likely to be successful. In framing the problem, it is important to include the perspectives of individuals and interested parties whose voices and concerns might not otherwise be heard, those who will assume the responsibility of administering and implementing the adaptation and sustaining it over time, and those involved in monitoring success or failure against stated goals and objectives. In coping with uncertainty, it will be particularly important to separate relevant signals from random noise in the observations, carefully analyze new scientific information, and design "midcourse" adjustments based on lessons learned (***NRC, 2010***).

2.3.5 *Agriculture and Greenhouse Gases*

One of the most important resources society depends upon is agriculture. With so much irrefutable evidence demonstrating that global warming is indeed occurring and that ecosystems worldwide are already feeling the effects and having to adapt, the protection of agricultural resources is critical. Without the successful adaptation of agriculture and livestock to the long-term changes of climate due to global warming, future adaptation for anything would be difficult. Agricultural systems are influenced by several environmental factors—especially weather and climate. Agriculture and livestock depend on the health and well-being of soil conditions such as the presence and quality of organic matter and availability of adequate moisture. If the progression of global warming upsets the balance of any of these biophysical properties (precipitation, temperature, soil moisture, and organic matter), agriculture and livestock will be negatively affected.

Global warming will have an effect on agriculture worldwide, but the outcomes will not be consistent. There may be positive effects in some areas and negative ones in others. As global warming influences temperatures and precipitation, it will play an important role in what types and amounts of crops can be produced. This will have a crucial effect on the world's food supply—what can be grown, how much, and where. Currently, much of the work done to understand global warming and determining how specific areas may change is through computer modeling. Modeling climate change is very complicated, however. Precipitation patterns and cloud formation and movement are currently very difficult to model because clouds are small-scale features that move and change rapidly; modeling is most successful on the mechanisms of climate that occupy larger scales and move slower, such as massive air masses like the global circulation patterns of jet streams, westerlies, and *trade winds.* Biophysical factors such as soil conditions and type and amount of organic matter help determine soil moisture and crop conditions. Climate change also reflects these ranges of conditions, which in turn affects crop production (***Casper, 2010***).

It is expected that, agricultural production will experience a mixture of positive or negative effects that will depend on the geography and specific conditions of the area. The effect of increased temperature can have either a positive or negative effect, based on geography. For instance, for the colder high latitude locations such as Alaska and Canada, warmer temperatures would enable the existence of longer growing seasons. This could encourage the possibility of extended growing seasons as long as soil conditions are adequate. If soil conditions are not adequate and are not fertile enough (lacking proper nutrients and soil structure) to support the growth of crops, the length of the growing season will not matter because growing crops would not be successful. Adding large doses of fertilizer to increase fertility is also not a good option because they can have negative effects on the environment, such as being washed off into the drainage and entering and polluting the water cycle and biogeochemical systems. In more southern latitude locations, warmer temperatures would be beneficial if they eliminated the killing frosts that can currently destroy crops. This could potentially enable citrus crops to be grown farther north. The U.S. Department of Agriculture warns, however, that high temperatures could shorten the critical growing period interval, limiting the successful growth of large crop yields. Changes in precipitation may also have positive and negative effects. Increased precipitation in the traditionally arid areas such as the American Southwest would benefit them by enabling growing periods to exist. On the other hand, precipitation increase in areas where it results in flooding would be a disaster, causing erosion and loss of land and resources. In other geographical locations that experience a shortfall of precipitation, drought and water shortage would cause havoc with agricultural production (***Casper, 2010***).

Accounting for greenhouse gas (GHG) emissions has emerged as an issue of considerable interest. While the scientific community is working for understanding of geochemical cycles, public policy is aiming to limit and decrease emissions and thereby to mitigate global climate change. The issues of monitoring and verification of international or sub-national commitments to reducing emissions are receiving increasing attention (***NRC, 2010***). Increasing levels of

CO_2 in the atmosphere usually increases the net photosynthetic rates in plants, as well as reduces transpiration loss. Because the photosynthesis rate is enhanced in plants as atmospheric CO_2 increases, vegetation productivity rises. The specific reaction to increased CO_2 to each plant varies by plant species. It is well known that, the main commercial crops grown in the United States are wheat, rice, potatoes, barley, oats, and a wide variety of vegetables, which typically respond well to an increase in CO_2. With a modeled increase of a doubled level of CO_2, crops in the United States would be expected to generally increase quantities by 15 to 20 percent. On the other hand, the tropical vegetation species—or warm weather crops—such as sugarcane, sorghum, corn, and tropical grasses are much less responsive and estimates of only 5 percent are expected. The difficult aspect of this modeling is that some scientists believe crop productivity is also significantly difficult to predict because CO_2 is also influenced by other things such as nutrients and water availability, which makes it more difficult to predict the future. In computer modeling done by the IPCC, the estimated effects of global warming on agricultural resources will vary from crop to crop and geographic region to geographic region (***Casper, 2010***; **Table 2.22**).

Table 2.22: Estimated climate change effects on crop yields in Latin and North America (adapted from ***Casper, 2010***)

Location of Study Site	Impact (Crop: Percent Change in Yield)
North America	
Canada	Wheat: –40% to +234% (results vary due to geographic location)
United States	Corn: –30% to –15%
	Wheat: –20% to –2%
	Soybean: –40% to +15%
Latin America	
Argentina	Corn: –36% to –17%
	Wheat: +3% to +48%
	Soybean: –3% to –8%
Brazil	Corn: –25% to –2%
	Wheat: –50% to –15%
	Soybean: –61% to –6%
Mexico	Corn: –61% to –6%

Note: Increases are due to cooler areas becoming warmer and more conducive to the growth of crops; decreases are due to areas becoming more arid and less conducive to the growth of crops.

General predictions have been made that areas that experience large temperature changes will experience more negative effects. Countries in the mid- and high-latitude areas may experience an enhanced CO_2 effect accompanied by an increase in agricultural production; but yields in low-latitude countries such as Brazil may actually see a decline in agricultural production, especially with commodities such as corn and wheat, as drought becomes more likely. The commodity that seems to be the most resilient to climate change is rice. According to the IPCC, specific temperature ranges may also play an important role. For instance, areas that increase up to 3.6°F (2°C) are the areas that may experience positive crop yields. Areas that have an increase of 7.2°F (4°C), on the other hand, may actually see less production. Livestock are also greatly affected by global warming. They can be affected in two major ways: (1) by the quantity of grazable land and whether there is enough to support the number of livestock on it; (2) the quality of grazable land—the types and abundance of forage available for the health of the livestock living on the land. Global warming can seriously affect both of these variables (***Casper, 2010***).

The Pew Center on Global Climate Change has also identified some indirect effects of climate change on agriculture. One of the most significant is soil erosion and degradation. The effects of flooding, drought, and wind erosion can have devastating effects on crop yields. **Casper (2010)** reviewed about the positive and negative effects of global climate change as shown in **Table 2.23**.

2.3.6 *Strategies to Combat the Impact of Climatic Changes*

The most important global debate of this century is on climate change. It is predicted that by 2050 there will be significant impacts including rising temperature, globally increased rainfall (~ 6%, ***Bengtsson et al. 2009***) but increasing drought due to higher evaporation and changing rainfall distribution, and increased levels of CO_2 due to greenhouse and agriculture gas emissions. Climate change predictions over this century are for warmer (at least 1–2 ºC) and drier conditions, with increased extreme weather events and increased CO_2 levels, in the regions where the principal temperate grain legumes of chickpea, lentil, faba bean and pea are mainly grown (***IPCC, 2007a; b***).

However, rainfall may increase at higher and some tropical latitudes (***Bengtsson et al. 2009***), and frost frequency may increase with drier conditions. Genetic adjustment of crops can help to mitigate the adverse effects on production, resulting from shorter crop cycles with warmer temperatures and reduced moisture, (***Anwar et al. 2007***) partly offset by growth response to increased CO_2. However, the negative impact of climate change will likely be far greater closer to the equator, in some of the world's poorest and most densely populated countries. Forecasts indicate that elevated CO_2 levels will have a fertilizing effect in some regions, although this will be negated by greater drought and heat stress in lower latitude areas (***Yadav et al. 2010***).

Table 2.23: Positive and negative effects of global climate change (adapted from ***Casper, 2010***)

Positive Effects of Climate Change	***Negative Effects of Climate Change***
According to a report in ***National Geographic News*** **(2002)**, as greenhouse gas levels climb higher in the atmosphere, crop yields may increase in certain areas, such as fruits, vegetables, seeds, and grains. Although this may initially sound like a good thing, the positive effect is short-lived because it also results in a decrease in the crop's nutritional value.	In fact, researcher **Frank Mitloehner** of the University of California has eight cows confined inside what he refers to as a "bio-bubble" (a big white tent) to answer an extremely important question: How much gas does a cow actually emit?
Peter S. Curtis, an ecologist at Ohio State University, says, "But there's a trade-off between quantity and quality. While crops may be more productive, the resulting produce will be of lower nutritional value."	According to **Mitloehner**, one of the most surprising results of the experiment was that the most significant greenhouse gas emissions were not a result of the manure. According to him, "We thought it was the waste that would lead to the majority of the [greenhouse gas] emissions, but it seemed to have been the animals."
Robert Mendelsohn, an environmental economist at Yale University, says, "There is no doubt but that quality matters. If scientists can demonstrate a distinct loss of quality, this would be important and could change our impression of the global impact of climate change on agriculture from benign to harmful."	The major contributor to greenhouse gases was the ruminating process. During a cow's digestion process, as food enters the stomach, it mixes with bacteria, which breaks the food down and produces methane. Roughly 20 minutes later, the food returns to the cow's mouth as cud, which it chews, thereby releasing methane into the air. In addition to methane, it also releases methanol and ethanol, as well as VOCs.
One of the key concepts **Peter Curtis** wanted to focus on was the overall reproductive traits of plants such as the number of seeds and fruit, their size, and their nutritional quality because researchers had already confirmed that increasing CO_2 levels did increase the growth of the plant's leaves, stems, and roots.	Another negative impact concerns manure management. The decomposition of animal waste in an anaerobic environment produces methane. According to the Environmental Protection Agency (EPA), manure storage and treatment systems are responsible for about 9 % of the total methane emissions in the United States, and 31 percent of the methane emissions coming from the agricultural sector alone.
The results of **Curtis** study showed that with a doubling of CO_2, total seed weight increased 25 %, the number of flowers increased 19 %, individual seed weight increased 4 %, and the number of seeds increased 16 %. The study did have some unexpected results, however. According to Curtis, "The surprise is that nitrogen levels actually go down with elevated CO_2 levels, which reduces the nutritional value of these foods because it lowers the protein content. In some cases, nitrogen levels were 15 – 20 % lower."	Methane has an enormous greenhouse gas potential. It is about 21 times more effective at trapping heat than CO_2. In fact, 10 % of the warming in the United States caused by global warming is due to methane alone. More than 80 percent of the methane emissions that originate from animal wastes come from liquid-based manure management systems that include: anaerobic lagoons, holding tanks, and manure ponds.
Irakli Loladze, an ecologist at Princeton University, says, "The increase in crop productivity does not make up for the fall in nutritional value of the crops—plants today provide 84 % of the calories people eat worldwide and are also the source of major essential nutrients." He also noticed that levels of micronutrients (such as Fe, Zn, and I_2) also dropped as CO_2 levels rose.	According to the EPA, one solution that has been suggested to combat this problem is the use of anaerobic digester systems. An anaerobic digester is a container similar to a covered lagoon that is designed to hold decomposing manure under warm, oxygen-free conditions that promote the growth of naturally occurring bacteria. The purpose of the bacteria is to digest the manure, producing methane and an effluent that farmers can use in place of untreated manure.
A study conducted by **Ramakrishna Nemani (2003)** at the University of Montana marked the first vegetation inventory and the effects of global warming as it relates to temperature and precipitation from a global perspective. They showed that global vegetation had	The by-product (methane) produced by these digesters is called "biogas," and it can now be used effectively as an energy source. Depending on how much they generate, they may also have the option to sell "extra" electricity directly to local utility companies. Secondary benefits

increased 6 % from 1982 to 1999. In the Amazon region, Nemani says a major cause of vegetation growth is due to less cloud cover, resulting in increased solar radiation. The Amazon region accounts for 42 % of the global increase. The atmospheric scientist **Dave Schimel**, who works at the National Center for Atmospheric Research in Boulder, Colorado, keyed in on the impacts due to absence of cloud cover and its significance for increased vegetation. According to Schimel, "Most studies of the effects of climate change have addressed temperature effects; some have also addressed water effects. But some of the most robust observed changes in climate have been in cloudiness and almost no studies have examined trends in solar radiation. So this is a really interesting new perspective."	include a reduction of odors, methane emissions, and surface/groundwater contamination. Farmers can also sell the resulting high-quality fertilizer. These related business opportunities help the overall position of U.S. agribusiness. Fertilizer management is another area of concern. Based on information collected by the EPA, the use of synthetic *nitrogen* and organic fertilizers has contributed to about 36 % of total U.S. nitrous oxide (N_2O) emissions. Nitrous oxide is about 310 times more effective at trapping heat in the atmosphere than CO_2. While most N_2O is produced naturally through microbial processes in the soil, it is the addition of synthetic N_2O introduced through fertilizers that has led to an increase in emissions from agricultural lands. According to the IPCC, if fertilizer applications are doubled, emissions of N_2O will double. Therefore, the IPCC has recommended that N-fertilizer be used more efficiently in order to reduce N_2O emissions.

To combat the impact of climate change in the years to come, so that world can survive, various approaches have been suggested differently world wide. However, in the context of agriculture, solutions to climate change involve two aspects: adaptation which suggest how to maintain production under changed conditions, and mitigation which explain how to soften the impacts on the most vulnerable communities. Thus various approaches have been mentioned to involve both the approaches. It could be summarized the strategies to combat the impact of climatic changes as follows (***Yadav et al. 2010***):

(1) *Governmental policies*

Climate changes are occurring in all the continents with many countries having either documented changes or predicted them by climate modeling (***IPCC, 2007a, b***). Various ecological imbalances are being recorded and documented by national and international organizations around the world. In response to these changes and predictions governments have already initiated many policy decisions to combat the influence of climate change. If these initiatives are to be successful it is important that they receive high priority. For example Japan, China, Australia, UK, Denmark, Bangladesh, Tunisia etc. have implemented policies aimed at mitigating the adverse impact of climate change. These government policies are essential otherwise it will be difficult to mitigate this impact globally (***Yadav et al. 2010***).

(2) *Reduction of CO_2 Emission*

Rising CO_2 levels are considered a precursor of climate change. CO_2 itself is the starting point for carbon fixation by the process of photosynthesis. It is well known from controlled-environment experiments that photosynthetic performance is enhanced by higher levels of CO_2 in the atmosphere because of the way the stomata operate. Field experiments have been set-up in several countries to examine the effects of elevated CO_2 during the cropping season and the approach is known as Free Air CO_2 enrichment (FACE). The general trend is that higher levels of CO_2 produce slightly higher yields, but different varieties may respond very differently. Also, the beneficial effects of higher CO_2 appear to be muted in drier environments (***ICARDA, Caravan, 2008***). The policies aimed at the development of emission reductions programmes and the provision of carbon offsets will create *the biggest impact in tackling climate change, globally.* Environmental and human needs mean real reductions need to happen now. However, it must be remembered that none of the **IPCC (2007a, b)** emission reduction scenarios allow us to avoid increases in global CO_2 levels. The successful implementation of CO_2 reduction emission needs following considerations around the world:

- Reducing large scale emissions in a business takes time, and offsetting alongside a reduction strategy has a greater immediate impact. Offsetting is the only way to deal with unavoidable large scale emissions and take responsibility for total emissions impact from day one. Many small scale point source emissions can be reduced without loss of productivity with existing technology (e.g. video link rather than driving) if there is a desire to do so.
- Developing a successful carbon market which helps allocate investment where it can make the greatest longer term impact. Businesses should support this. While there are still disagreements over the exact forms (cap and trade; baseline and credit) there is a need for an efficient global system.
- Funding the development of the new low carbon technologies which the world, especially the developing world, needs. This could create longer-term capacity, skills and knowledge, bringing wider benefits to local communities.
- Developing and promoting new management practices which reduce the carbon and nitrogen footprints by enhancing the long term storage of carbon in managed land while simultaneously reducing the emission of the other greenhouse gases: nitrous oxide and methane.

Thus it is important to halt the worsening of climate change effects by introducing limitations on greenhouse gas emissions at the international level by both the developing and developed world (***Yadav et al. 2010***).

(3) *Educating People and Strengthening National Organizations*

In order to ensure successful mitigation of the impact of climate change on field crops in general and legume crops in particular, effective and well supported, institutional mechanisms should be established at national and international levels. Thus effective means can be developed to take essential policy decisions around infrastructure development, resources mobilization, capacity building and implementation of technical programmes (***Yadav et al. 2010***).

(4) ***Breeding Strategies and Development of Cultivars***

It is imperative to develop breeding approaches so new cultivars can withstand or take advantage of climate changes in respect of high and low temperature, moisture stress, increase CO_2 levels, changes in seasonal temperature, light and rainfall distribution etc. To screen and identify resistant/tolerant donors it is essential to collect diverse germplasm lines including wild species and evaluate under the future probable environments. This could be achieved through the following ways:

- Focusing on dry lands and incorporation of drought Tolerance in crops
- Low and high temperature tolerance in crops
- Water use efficiency of crops

(5) ***Plant Modelling***

Because climate change will result in altered growing conditions there is a need to gain as much information as possible in a short period, often for future environments. One year at a time experiments will not be the most efficient method for doing this, so there is a great need to use crop modeling to understand the future needs of the crop. Research of this nature is being carried out (***Anwar et al. 2007***) however, there is a need to develop and apply increased use of plant modelling approaches that allow assessment of impacts of changes in climate, climatic variability and extreme weather events on pest, beneficial and endangered insects, arable plant communities, plant diseases and the sustainability of crop production (***Yadav et al. 2010***).

(*6*) ***Integrated Production Management Technologies***

In the last 50 years, attempts to overcome biotic constraints of crop production have mainly focused on use of chemical pesticides and/or host- plant resistance. These single – factor management strategies to combat biotic and/or abiotic constraints have often been studied in isolation from each other. As a result the yield losses caused by pests or diseases epidemics, along with poor agronomy, have remained alarming and significant. There is a greater opportunity to combine best technologies that combat insect-pests and disease with improved agronomical practices and emerge with integrated management packages. Integrated management packages for crops provide greater scope and need validation, up-scaling and out-scaling with the involvement of farmers. Thus combining of different technologies like desired agronomic management including weed and irrigation management, disease management, insect and pest integrated management, development and incorporation of high yielding resistant, widely adapted and quality cultivars are essential. Under changing climates the implementation of integrated production management technologies is very important to sustain the productivity of crops globally. The understanding of regional impacts of climate change on crops is important in relation to knowing the predicted impact of climate change (***Yadav et al. 2010***).

3 *Impacts of Climate Changes on Soil, Water and Air Environments*

"وَلَوْ أَنَّ أَهْلَ الْقُرَى آمَنُواْ وَاتَّقَواْ لَفَتَحْنَا عَلَيْهِم بَرَكَاتٍ مِّنَ السَّمَاءِ وَالأَرْضِ وَلَـكِن كَذَّبُواْ فَأَخَذْنَاهُم بِمَا كَانُواْ يَكْسِبُونَ" الأعراف الآية 96

"And if only the people of the cities had believed and feared Allah, We would have opened upon them blessings from the heaven and the earth; but they denied [the messengers], so We seized them for what they were earning"

(***Holy Quran***: Al-A'aaf, verse **96**)

3. Impacts of climate changes on soil, water and air environments

3.1 *The role of soils in climate changes*

Soil use and management produce several goods including food, feed, fiber, fuel, and industrial raw materials. .Under both natural and managed ecosystems, soils also generate numerous ecosystem services including moderation of climate, purification and filtration of water, enhancement of biodiversity, an archive of planetary and earth history, a reservoir of germplasm, etc. Whereas soil degradation may lead to reductions in its ability to produce goods and generate services, its capacity to do so also depends on numerous endogenous and exogenous factors. Endogenous factors are those related to soil-forming factors including climate, vegetation, parent material, terrain, and time. The exogenous factors include anthropogenic perturbations including deforestation, biomass burning, drainage, irrigation, and use of inputs (fertilizer, amendments, tillage methods, residues management, vehicular traffic, cropping and farming systems, etc). Exogenous factors may also be natural perturbations such as volcanic eruption, seismic activity, tsunami, etc. The impacts of exogenous factors on the extent and severity are exacerbated by several endogenous factors (i.e., climate, terrain) (***Lal and Stewart, 2012***).

Soils form through the interaction of a number of influences, including climate, relief and/or landscape, parent material, organisms (including fauna, flora, and humans) and time. The nature of this interaction varies in different parts of the world, resulting in several thousand types of soil worldwide. It takes thousands of years for a soil to form, and most soils are still evolving as a result of changes in some of these soil-forming factors, particularly climate and vegetation, over the past few millennia. Changes in any of the soil-forming factors, such as climate, will impact directly and indirectly on current soils, with important implications for their development and use (***Bullock, 2005***).

The earth's biosphere constitutes a bio-thermodynamic machine that is driven by solar energy and the exchanges of water, oxygen, carbon dioxide, and other components in the pedosphere–hydrosphere–atmosphere continuum. Green plants in the terrestrial domain perform photosynthesis by absorbing atmospheric CO_2 and reducing it to forms of organic carbon in combination with soil-derived water, while utilizing the energy of sunlight. In the process, radiant energy is transformed into chemical energy that is stored in the molecular bonds of organic compounds produced by the plants. This in turn provides the basis for the food chain, which sustains all kinds of animal life. Roughly 50% of the carbon photosynthesized by plants is returned to the atmosphere as CO_2 in the process of plant respiration. The rest, being the carbon assimilated and incorporated in leaves, stems, fruits, and roots, exists as standing biomass or is deposited on or within the soil. There, organic compounds are ingested by a diverse biotic community, including primary decomposers (bacteria and fungi) and an array of mesofauna and macrofauna (nematodes, insects, earthworms, rodents, etc.). The ultimate product of organic matter decay in the soil is a complex of relatively stable compounds known collectively as *humus*. It generally accounts for some 60 to 80% of the total organic matter present, the balance consisting of recent organic debris of partially decomposed litter, dead roots, and the waste products of soil fauna (***Hillel and Rosenzweig, 2011***).

Climate change is predicted to seriously impact many of the world's major cropping areas. The majority of the world's food and fibre is produced in cropping systems, and increasing food production to meet the needs of the increasing world population in an environment of uncertainties about climate change is going to be a major challenge facing communities (***Wentworth Group, 2009***). Maintaining crop productivity is a key element in meeting these future challenges, and this will rely largely on maintaining soil health. Some of the expected impacts of climate change on cropping areas include (***IPCC, 2007a***):

- Reduced total effective rainfall, which will change the potential amount of biomass produced and the amount of ground cover;
- Changing rainfall patterns with increased rainfall intensity and erosivity;
- Higher temperatures and evapotranspiration rates.

In response to these predictions, the adaptive land management strategies being investigated include varying planting time, sowing rates, nitrogen application, cover and crop varieties, residue management, tillage type and depth, and length of fallow. Improvement in soil health through the adoption of best management strategies will have a profound positive impact, providing resilience and flexibility to meet the challenges of climate change and variability. For example, adopting conservation cropping practices with less soil disturbance and maintaining greater levels of crop residues has the potential to maintain and improve soil health, through positive impacts on key soil properties or processes and consequently increasing agriculture sector's ability to adapt to climate change (***Murphy et al. 2011***).

Raison and Khanna (2011) adopted the following definition of climate change used by the Intergovernmental Panel on Climate Change **(IPCC) (2007)**, and also include increasing atmospheric concentrations of CO_2 because of their likely major impact on the carbon cycle in forest ecosystems. Although increased N deposition is also often a consequence of the same human activities that result in greenhouse gas (GHG) emissions and climate change, and can have significant impacts on soils (***Reay et al. 2008***), it is not considered in this chapter. Climate change in IPCC usage refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of climate properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change in the climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (**Tables 3.1 and 3.2**).

Table 3.1: Timescale for changes in soils with change in climate (adapted from ***Bullock, 2005***)

Timescale categories	Soil parameter	Properties and characteristics	Regimes
< 10^{-1} years	Temperature; moisture content; bulk density; total porosity; infiltration rate; permeability; composition of soil air; nitrate content	Compaction; drainage; workability	Aeration; heat regime
10^{-1}–10^{0} years	Total water capacity; field capacity; hydraulic conductivity; pH; nutrient status; composition of soil solution	Microbiota	Microbial activity; human controlled plant-nutrient regime; erosion
10^{0}–10^{1} years	Wilting percentage; soil acidity; cation exchange capacity; exchangeable cations	Type of soil structure; annual roots biota; mesofauna; litter, fluvic, gleyic, stagnic properties; slickensides	Moisture; natural fertility; salinity–alkalinity; desertification; permafrost
10^{1}–10^{2} years	Specific surface; clay mineral association; organic matter content	Tree roots; soil biota; salic, calcareous, sodic, vertic properties	
10^{2}–10^{3} years	Primary mineral composition; chemical composition of mineral part	Tree roots; color (yellowish/reddish); iron concretions; soil depth; cracking; soft powdered lime; indurated subsoil	
> 10^{3} years	Texture; particle-size distribution; particle density	Parent material; depth; abrupt textural change	

It is well known that soil and environmental conditions interact to define regional patterns in agricultural systems creating agricultural ecological differing homogeneous regions (agro-ecoregions), such as the Corn Belt (USA), Wheat belt (Western Australia), etc. It appears that current uptake of organic (and other alternative) agricultural system is driven by a combination of factors in both the physical and socio-economic environment which interact with personal farmer motivational factors. **Hendrickson et al. (2008)** suggested that there are other factors, such as landform, length of growing season coupled to the availability of irrigation that predispose farmers to adopt integrated low-input systems as a strategy to provide economic stability in variable conditions. While climatic regions set some constraints to the adoption of particular practices or agricultural systems, it is clear that the direct impacts of climate change will be only one driver of change in farming systems; changes in markets and agricultural policy will have an equally significant impact.

Modelling of climate change indicates that for most regions there will be changes in both means and extremes of temperature and rainfall which will affect the designation of current agro-ecoregions (***Lobell et al. 2008***). However, it is important to note that in any region, day length will not be affected and consequently, for some crops, suitability regions may not simply move towards higher latitudes. **Porter and Semenov (2005)** showed using experimental data and modelling that negative impacts on the yield and quality of wheat would occur more often than under current conditions. They also showed that increased occurrence of short periods of extreme temperatures or precipitation would have significant impacts on crop development especially C and N sink formation and activity.

Table 3.2: Soil functions and climatic change (adapted from ***Bullock, 2005***)

Function	*Use of soils*	*Impacts of climate change*
Economic	Food crops, energy crops, timber Sand, gravel, minerals Foundations for buildings, roads, etc.	Changes in land-use capability Changes of productivity Erosion and salinization Nitrate leaching and increased use of fertilizers (wetter conditions) Need for increased irrigation (drier conditions) Changes to foundations of buildings Higher building insurance premiums
Ecologic	Habitats for soil fauna and microflora Food for ground feeders, e.g., birds Nutrient supply and storage Cycling of water and air	Loss of some habitats Stress on many habitats Changes in soil biodiversity Likely loss of soil organic matter Changes in soil fertility Acidification (wetter conditions) Loss of peat habitats (drier conditions)
Hydrologic	Water storage, flow control and runoff, absorption, amelioration	Water resources problems (drier conditions) Transfer of salts Transfer of nutrients Increased bypass flow (drier conditions) Erosion sediment transfer
Pollutant control	Source and sink for pollutants Waste disposal medium	Increased bypass flow (drier conditions) Erosion and movement of pollutants Changes between sources and sinks
Gaseous exchanges	Source and sink of greenhouse gases	Increased decomposition of organic matter (CO_2 release) Sequestration of carbon Increased/decreased N_2O release (wetter/drier conditions) Increased/decreased CH_4 release (wetter/drier conditions)
Heritage protection	Protection of buried archeological sites	Effects of erosion and sedimentation Loss of peat Cracking

Changes in climate at any location will also modify the ability of the crops to respond to other factors, for example increased nutrient supply or improved plant protection (***Porter and Semenov, 2005***). **Porter and Semenov (2005)** showed by modelling that the predicted changes in climate will have relatively little impact on average cereal yields in the UK; the largest impacts on yield are expected to occur where crops are currently being grown close to the edge of the climatic optimum, for example wheat may not be cultivable in the Mediterranean by 2050.

In each region climate/soil interactions will hold the key in determining the suitability of current cropping patterns and farming systems under changing climates. Furthermore, direct climate change impacts on crop choice and rotation design will be largely indistinguishable for organic and conventional systems. Nevertheless, organic systems are likely to be more resilient to the anticipated impacts of climate change on temperature and rainfall, due to changes in organic matter and soil structure that currently increase resilience to drought.

Climate change factors will impact on the physiological processes, activity and phenology of pests and their natural enemies (***Stacey, 2003***). However, accurate prediction of likely impacts depends on how all the species involved (plant, pest and predator/parasite) react to changing patterns of temperature, humidity and cloud cover (***Stacey, 2003***). This may lead to different patterns of disease/pest risks, new pest and diseases and failure in existing methods of pest control including biological control. **Stacey (2003)** suggests that increased variability in weather patterns will result in increased difficulty for farmers in designing management practices, which reduce pest control impacts on yield and/or quality due to the complex interactions between biological and environmental factors. Climate change impacts on pest and disease risk will be largely indistinguishable for organic and conventional systems; however, the multi-factorial approach to develop networks of partial solutions for pest and disease management routinely used in organic systems are likely to become more common in conventional systems (***Stockdale, 2011***).

3.1.1 *Introduction*

World soils, the basis of all terrestrial life, are finite in extent, variable over time and space, and prone to alterations by natural and anthropogenic perturbations. Productive soils of high quality are essential to human well-being, economic and sustainable development, political stability, and ethnic and cultural harmony. Ancient civilizations and cultures arose and thrived on good soils, and survived only as long as soils had the capacity to support them. These and other once thriving civilizations collapsed with declines in the quality of their soils. Even during the 21st century, a good soil is the engine of economic development and essential to present and future food security. Yet, the quality of soil resources is threatened by human-induced and natural perturbations. Soil quality is degraded by land misuse and soil mismanagement. Soil resources available for agricultural use are also being diminished for conversion to other uses (e.g., urbanization, industrial, recreational) (***Lal and Stewart, 2012***).

Soil and water resources, essential to the wellbeing of humanity, are severely degraded and polluted. Degradation of natural resources, caused by misuse and mismanagement, is intertwined with poverty and desperateness. Poor people do not care about stewardship, and pass on their sufferings to the land. Extractive farming is the principal cause of mining soil fertility and depleting carbon resources. There is a need for developing strong ethics for sustainable management of soil, water, and natural resources. The importance of the quality of soil, water and air for welfare of the biosphere in general and of the human in particular has been recognized for millennia. Yet, these three vital components of the environment have been taken for granted; misused, abused and exploited for short-term material gains; and often ignored and left to fend for themselves. The importance of using modern and innovative technologies cannot be overemphasized. In the context of improving agriculture in Sub-Saharan Africa, it is important to refer to the Law of Marginality. It states that *marginal soils cultivated with marginal inputs produce marginal yields, support marginal living, and create marginal environment prone to physical, social and economic instability* (***Lal, 2009***).

This chapter presents what we know about the current climate change, what is projected to occur in the future, the uncertainties of these projections, the methods for increasing the spatial resolution of projections of future climate, and how these estimates of climate change have been used in determining the potential effects on agriculture.

3.1.2 *Climate Changes and Soil Health*

Soil health refers to the capacity of soil to perform agronomic and environmental functions. Important among these functions are: agronomic/biomass productivity, response to management and inputs, and resistance to biotic and abiotic stresses. With reference to agricultural land use, soil health refers to its capacity to sustain and support growth of crops and animals while also maintaining and improving the environment. Such definitions of soil health imply an integrated holistic or system level approach, and are based on the concept that the whole is bigger than sum of its components. Key components include soil properties, processes, and synergistic interactions among them. An integrated approach considers soil as a living system which responds to managerial interventions as does an organism (***Kibblewhite et al. 2008***). It is in this context that the concept of soil health is similar to that of human health, and is determined by maintenance at an optimum level of key soil properties and processes. Key soil properties important to maintaining good soil health include favorable soil texture and structure or tilth, good internal drainage, optimal water, and nutrient retention capacities and soil reaction. Relevant soil processes include good aeration, low susceptibility to erosion, and strong nutrient cycling. An optimal level of soil organic matter (SOM) content is essential to all key soil properties and processes, which are strong determinants of soil health (***Lal, 2011***).

To be in good health, a soil must also be relatively free from pests and pathogens including nematodes and weeds, and have adequate nutrient reserves and suitable elemental concentrations and balance. A healthy soil must also have strong resistance to degradation processes and able to recover following a perturbation because of inherent resilience. The term "***soil health***" is primarily used by farmers, land managers, extension agents, and other practicing professionals. In comparison, the term "***soil quality***" is used by soil scientists and ecologists (***Karlen et al. 2003***). Soil health denotes numerous functions and ecosystem services provided by a soil. Important among ecosystem services are net primary production (NPP), denaturing, and filtering of pollutants to purify water, improving air quality by scrubbing contaminants, enhancing the environment, and moderating climate at local, regional, and global scales. Therefore, soil quality is assessed by identifying and measuring some key parameters (**Table 3.3**; ***Lal, 2011***).

Because of a strong similarity and often interchangeable use of these terms, several indices of assessing soil quality are also used to assess soil health (**Table 3.4**). Soil health is assessed using a composite soil health index and several biological indicators (**Table 3.4**). These key parameters are specific to three distinct but interrelated components: physical, chemical, and biological (**Figure 3.1**). The strong interaction among these components (i.e., biophysical, biochemical, and physicochemical) determines soil quality/soil health. However, the same parameters are also relevant to denote soil health, although used in somewhat descriptive and qualitative terms. The term "soil quality" is used under both natural and managed ecosystems, while "soil health" is used for soils managed to grow crops and pastures. Management, characterization, and knowledge about SOM pool are equally important in describing soil health or assessing soil quality. Cycling of carbon (C) through atmosphere–plant–soil continuum, and its transformation and retention among these components (**Figure 3.1**), is important to soil health. The C cycle is also important to gaseous composition of the atmosphere, the global climate change, and quality of water as moderated by fate and transport of pollutants and sediments (***Lal, 2011***).

Choice of strategies for managing soil health depends on the land use, antecedent soil properties, the desired function of interest to humans, and the required ecosystem services. Key soil properties and processes that impact soil health in agricultural, urban, and mine land ecosystems are outlined in **Figure 3.2.** Three components of soil health (i.e., physical, chemical, and biological) are also important to sustainable management of croplands and grazing/pasture lands. Soil physical health depends on texture, structure, rooting depth, drainage, available water capacity, erodibility, and heat capacity which moderates soil temperature (***Lal, 2011***). Determinants of soil chemical health include soil pH, nutrient reserves, surface charge properties, salt concentration and electrical conductivity, and elemental balance. Soil biological health is fundamental to microbial transformations of biomass C into humus and fluxes of green house gases (GHGs) into the atmosphere. Key determinants of soil biological health are magnitude of the SOC pool and its composition, microbial biomass C, soil biodiversity, and prevalence of soil-borne pathogens. In agricultural ecosystems, the goal of soil health management is to maintain and enhance agronomic productivity and economic profitability, and the strategy may differ among land uses and cropping systems (***Bell et al. 2007***).

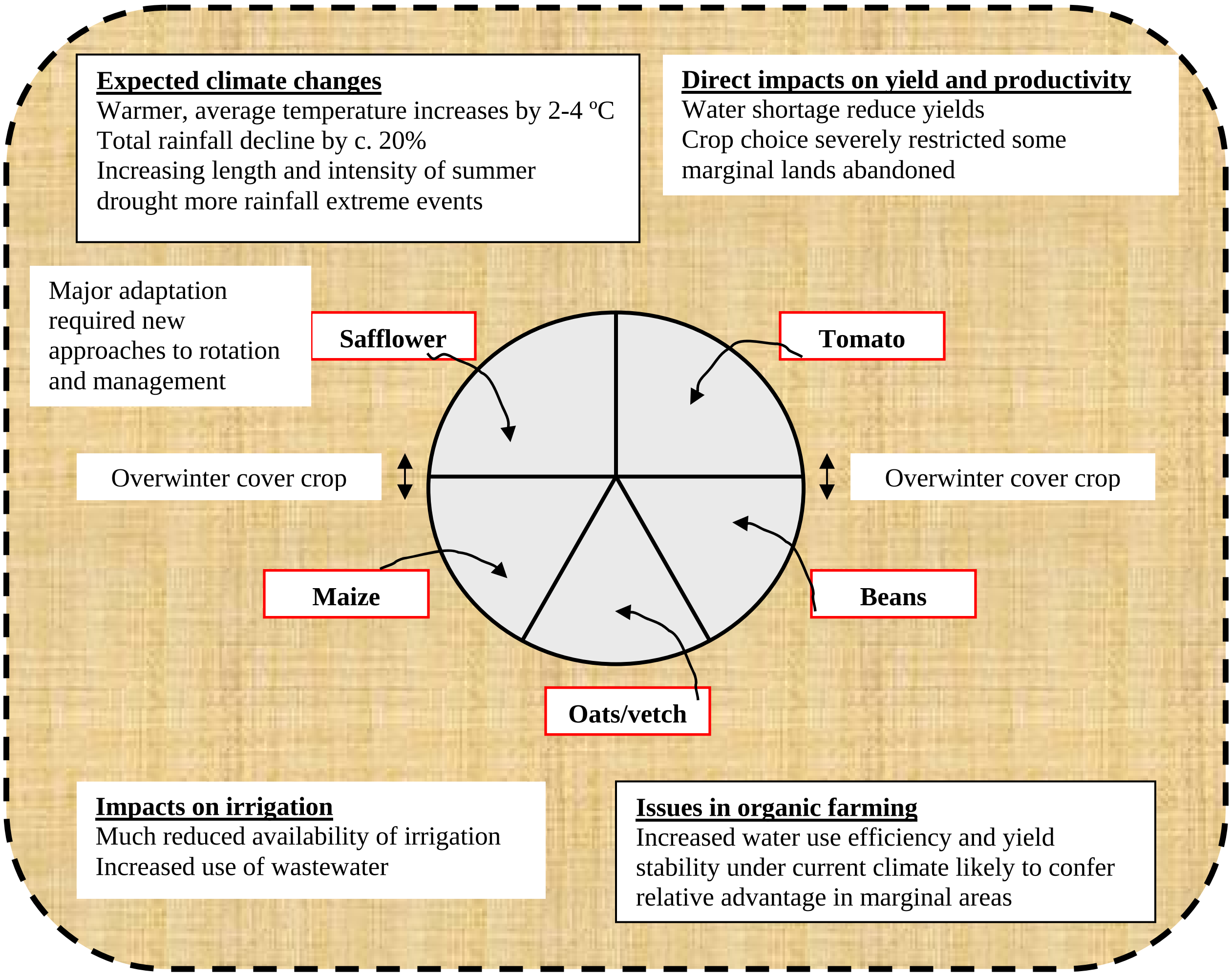


Figure 3.1: Predicted climate change and its direct and indirect impacts for a typical 4-year organic rotation common in Mediterranean climates. Issues for organic farming systems highlighted (adapted from ***Stockdale, 2011***)

Atmospheric concentration of CO_2 has increased by 39% from 280 ppm in the pre-industrial era to 390 ppm in 2010, and the present concentration exceeds the range observed over the last 65,000 years (***IPCC 2007a***). Increase in the concentration of CO_2 and other GHGs (CH_4, N_2O) has increased the global mean temperature by 0.76 ± 0.19 ºC over the twentieth century (***IPCC 2007a***), and with the business as usual, increase in global temperature by the end of the twenty-first century may be 4 ± 2 ºC with severe adverse impacts on biomes and the ecosystems services (***Lal, 2011***).

Soils have been a major source of atmospheric CO_2 and other GHGs (i.e., CH_4, N_2O) ever since the dawn of settled agriculture (***Ruddiman, 2005***). The magnitude of CO_2-C emission from soil to the atmosphere since the industrial revolution (~1750 AD) is estimated at 78 ± 12 Pg. Most soils under agricultural land use contain lower SOC pool than their counterpart under natural/ undisturbed ecosystems because of: (1) lower amount of biomass and detritus material returned, (2) higher decomposition rate attributed to changes in soil temperature and moisture regimes, (3) more leaching losses of the dissolved organic C (DOC), and (4) severe losses by accelerated wind and water erosion. Indeed, there is a large flux of CO_2 from the oxidation of SOM from agricultural soils. Thus, most cropland soils have lost 25–75% of their original SOC pool (***Lal, 2011***).

The soil organic C (SOC) concentration also improves adaptation to climate change by enhancing soil health and its buffering capacity. Enhancement of the SOC concentration, beyond the critical or threshold range, enhances soil health by: (1) improving soil structure and tilth, (2) enhancing plant available water capacity and reducing droughtiness, (3) increasing soils resistance to erosion and reducing erodibility, (4) increasing nutrient retention and availability, (5) increasing water infiltration rate and reducing surface runoff, (6) improving water quality and reducing nonpoint source pollution, (7) increasing soil biodiversity by providing food and habitat for soil biota, (8) reducing sedimentation in waterways and reservoirs, (9) improving use efficiency of inputs, and (10) increasing crop/plant growth and yield. It is also the improvement in soil health through SOC sequestration that is essential to increasing agronomic production and advancing food security (***Lal, 2006***).

The strong link between soil health and global climate is moderated through storage and emission of carbonaceous (CO_2, CH_4, soot), nitrogenous (N_2O, NO_x), and other organic and inorganic compounds. How humans manage soils influences the production and emission of these gases. The magnitude of gaseous emission is also influenced by the prevailing climate. Thus, there is a positive feedback relating gaseous emissions from soils to changing climate. Climate change and global warming may affect human health through shifts in the geography of vector-borne diseases such as malaria, dengue, and schistosomiasis. Changes in weather patterns may also exacerbate food and water shortages, increase the thermal-related mortality, and aggravate respiratory problems (**Table 3.5**; ***Lal, 2011***).

Table 3.3: Parameters to measure soil quality/soil health and express soil health (adapted from ***Lal, 2011***)

Quantifiable soil quality parameters	Qualitative soil health characteristics
Particle size distribution	Texture. feel
Water stake aggregation, mean weight diameter	Tilth, cloddiness
Pore size distribution and total porosity	Internal drainage
Water retention capacity	Droughtiness, inundation
Erodibility	Prone to erosion
Infiltration capacity/rate	Time to ponding
pH	Taste, smell
Cation/anion exchange capacity	Buffering
Electrical conductivity	Salinity
Nutrient concentration and availability	Fertility
Soil organic carbon concentration	Color, smell
Microbial biomass carbon	Biodiversity
Time to recover/restore following disturbance	Resilience

Table 3.4: Assessment of soil health at different scales (adapted from ***Lal, 2011***)

Soil quality/health index	***Scale***	***Application***	***Reference***
1. Composite soil health index (CSHI)	Field plots	Assess impact of tillage, rotation	Idowu et al. (2009)
2. Soil biological quality	Field plots	Response to crop management	Gil et al. (2009a, b)
3. Holistic assessment of soil quality	Landscape	Urban ecosystems	Schindelbeck et al. (2008)
4. Soil quality index (SQI)	Watershed	Impact of conservation practices	Karlen et al. (2008)
5. Short-term indicators	Landscape	Mulch management for vegetables	**Mochizuki et al. (2008)**
6. Soil biological quality	Field plot	Impacts of pesticides	Korthals et al. (2005)
7. Soil health dynamic	Field plot	Rotation and cover crop impacts	Carter et al. (2003)
8. Biological indicators	Field	Organic farming impact	Stockdale and Watson (2009)
9. Biological indicators	Landscape	Rainfed farming, tree crops	Moreno et al. (2009)
10. Chemical and biological parameters	Field	Impact of organic farming	Van Diepeningen et al. (2009)
11. Soil organic carbon	Field	Agricultural land use	Farquharson et al. (2003)

Table 3.5: Management practices to enhance soil organic pool and improve soil health and mitigate climate change (adapted from ***Lal, 2011***)

Country	***Soil***	***Management practices***	***Reference***
India	Inceptisols	Crop residue management, organic amendments	Mandal et al. (2007)
USA	–	Corn stalk return, no-till	Hooker et al. (2005)
	Alfisols	Mulch	Duiker and Lal (1999)
Australia	Vertisols	Stubble management, fertilization, no-tillage	Farquharson et al. (2003)
China	Black soils (Mollisols)	Manure, rotations, straw management	Liu et al. (2003)
	Alluvial (Yangtze Plains)	Manure, crop residues, conservation tillage	Rui and Zhamg (2010)
UK	–	Conservation agriculture, straw management	Hazarika et al. (2009)

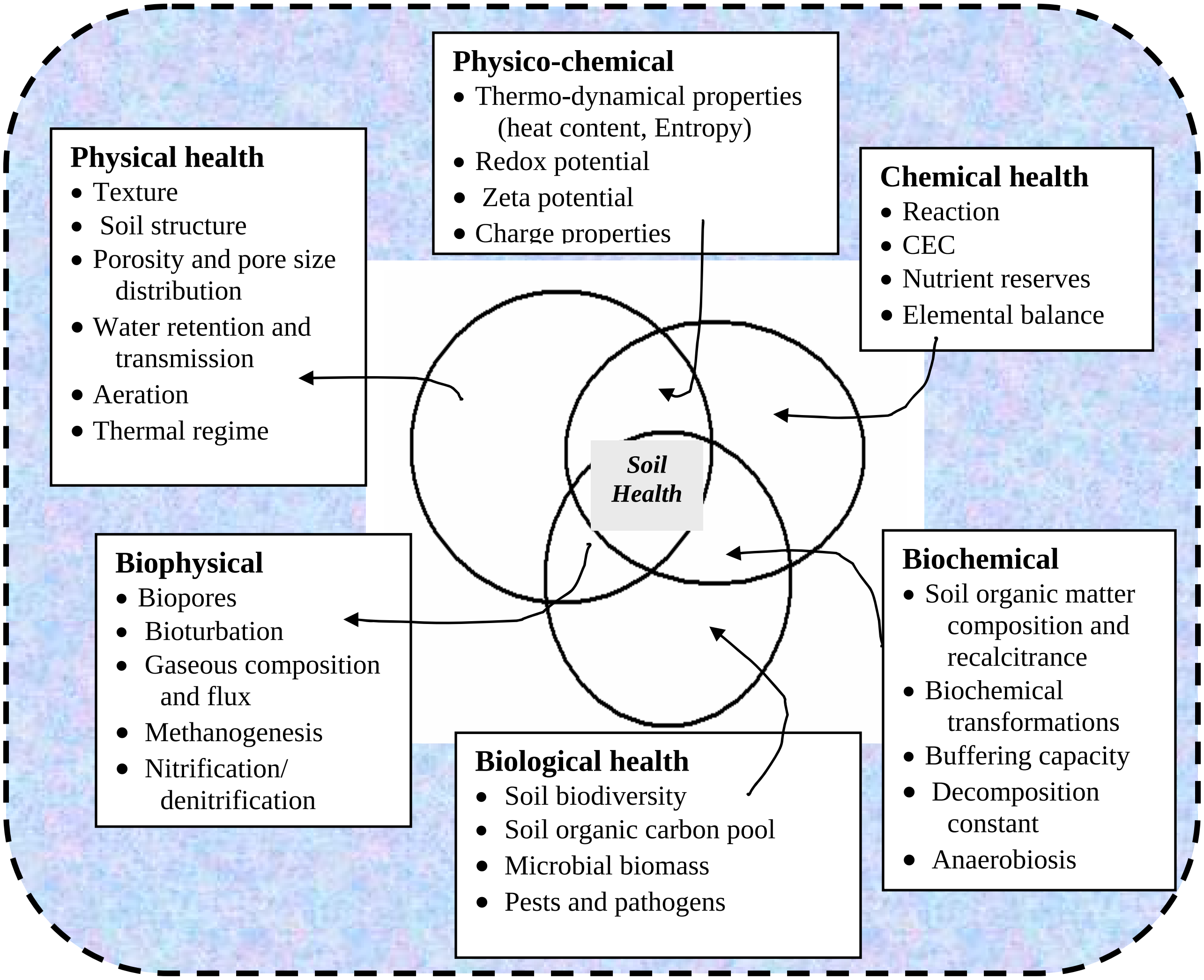


Figure 3.2: Components of soil health (adapted from ***Lal, 2011***)

Lal (2011) concluded the impacts of climate changes on soil quality (or health) as follows: soil health, capacity of a soil to produce agronomic and economic goods and services while also maintaining the environment quality, is a term used by farmers and land managers. In comparison, the term soil quality is used by soil scientists, agronomists, and pedologists. Key indicators of soil health, similar to that of soil quality, are soil structure, soil organic carbon concentration and quality, water retention and intake rate, and soil biodiversity. Thus, maintaining and enhancing these soil properties above the threshold/critical levels are essential to sustaining/improving soil health. Enhancing the soil organic carbon pool also improves agro-ecosystem resilience, eco-efficiency, and adaptation to climate change. Technical potential of soil C sequestration through improvement in soil health is ~3 Pg/year for about 50 years with a drawdown capacity of reducing atmospheric CO_2 concentration by 50 ppm over the twenty first century. Improving soil health, through restoration of degraded/desertified soil and adoption of recommended management practices (RMPs), is also a necessity to feeding the world population of 9.2 billion by 2050.

3.1.3 *Impact of Climate Changes on Soil Structure*

In terrestrial ecosystems and agro-ecosystems, soil structure determines soil physical fertility which is the capacity of the soil to support and sustain plant production in relation to its physical properties. Hence, soil structure plays a fundamental role in controlling physical soil health, productivity and environmental quality (on-site as well as off-site) of agricultural land. However, soil structure in agro-ecosystems is sensitive to human disturbance and therefore to management practices. Soil structure refers to the architecture and hence the arrangement of the solid phase of the soil and of the pore space located between its constituent particles. This architecture of soil (the structural form) determines not only the density of packing of the solid phase (bulk density) and hence total porosity, but more importantly also pore size distribution and pore continuity of the soil profiles. The importance of surface soil structure in controlling processes at the interphase of atmosphere, hydrosphere and geosphere, such as the processes of infiltration, and runoff, cannot be over-emphasized (***Chan, 2011***).

Climate change scenarios considered by Intergovernmental Panel on Climate Change (IPCC) prediction include increase in atmospheric CO_2 concentration, increases in air temperature, changes in precipitation and prevalence of extreme climate events. For instance, global temperature change of 1.6–6.4 ºC by 2100, atmospheric CO_2 concentration increases by up to 550 ppm and precipitation change by at least 20% have been predicted (***IPCC, 2007a***). However, the predicted changes vary geographically and with future greenhouse gas (GHG) emission control. Therefore, the actual magnitude of changes of these parameters and consequences of these changes will therefore be location specific and be dependent on the extent of future success in reducing emission of GHG. Changes in precipitation are likely to be different for different parts of the world.

Over the twentieth century, precipitation has mostly increased in high northern latitudes, while decreases have dominated from 10ºS to 30ºN since the 1970s. There is high confidence that many areas in the subtropics and temperate regions, namely Australia, Mediterranean Basin, western USA, northwest and South-West Africa, and north-eastern Brazil will suffer a decrease in precipitation due to climate change (***IPCC, 2007a*; Figures 3.3 and 3.4**).

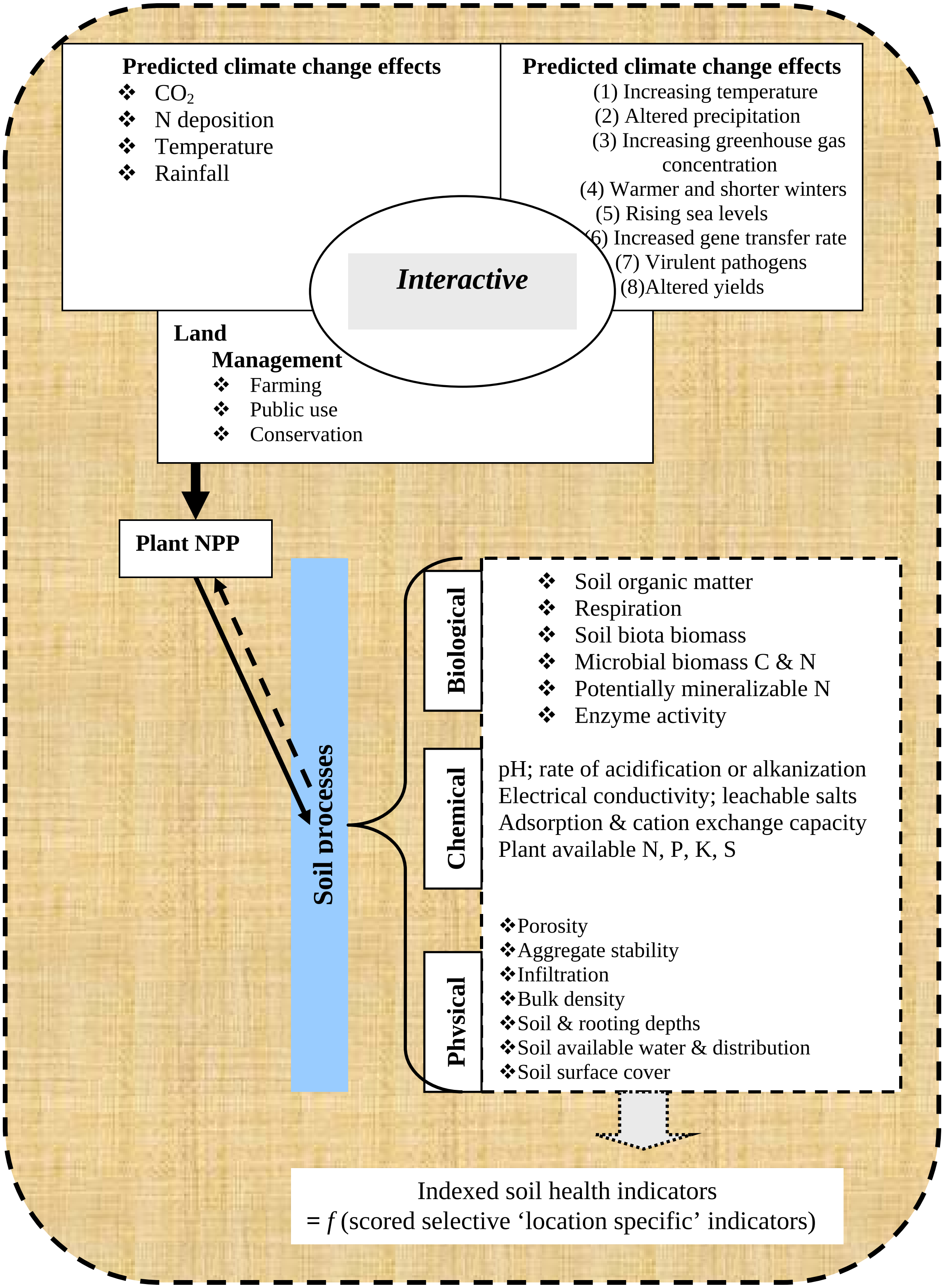


Figure 3.3: Schematic representation of the potential links between climate change, land use and management change, and soil health indicators (adapted from ***Allen et al. 2011***)

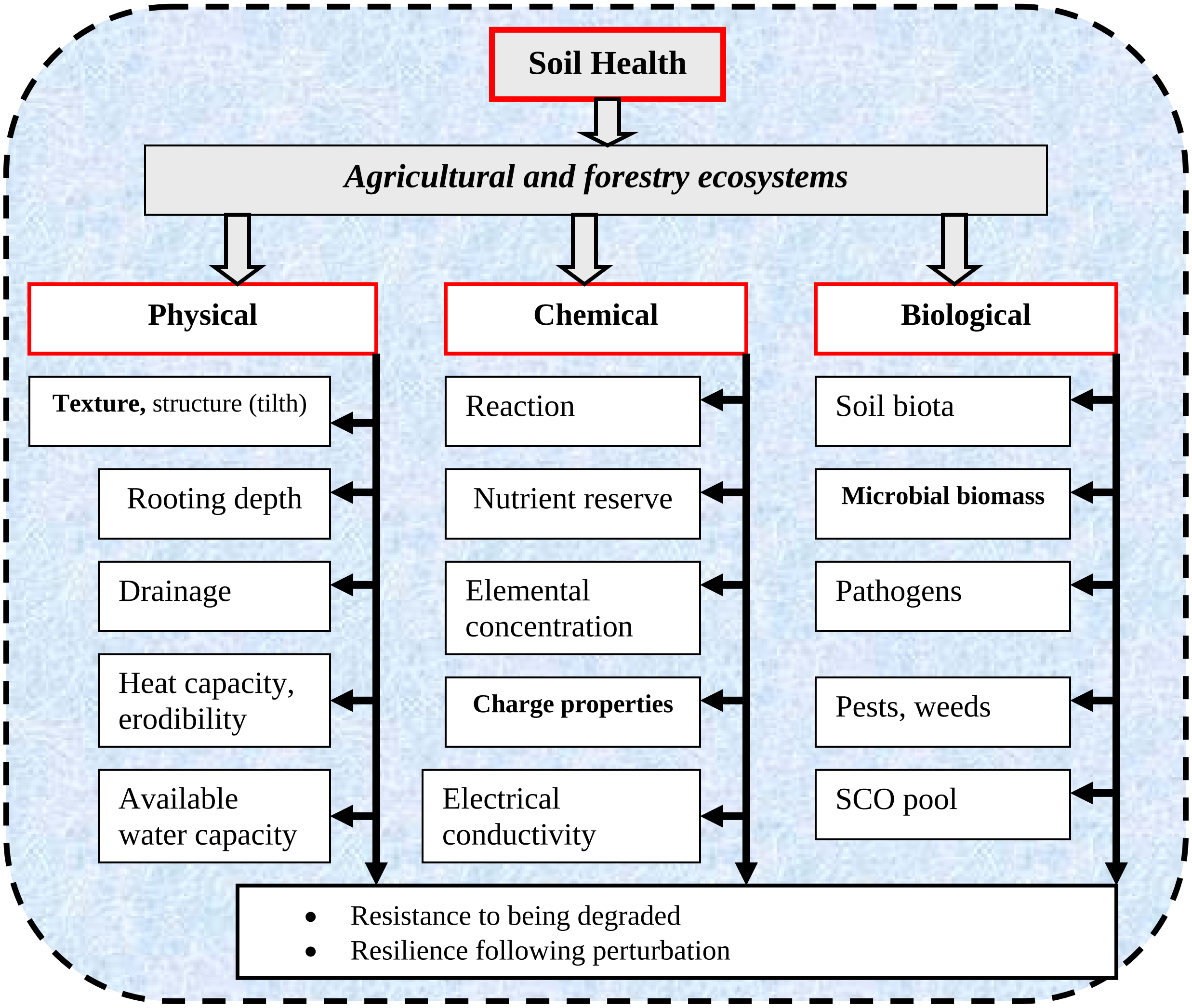


Figure 3.4: Concepts of soil health for agricultural and forestry ecosystems and functions (adapted from *Lal, 2011*)

Climate changes can affect all the three aspects of soil structure (form, stability and resilience) both directly and indirectly as follows:

I. *Direct impacts of climate changes on soil structure:*

With the predicted climate changes, soils are expected to be exposed to drier environment for longer period of time and, on the other hand, more likely to be subjected to more intense rate of wetting and flooding. Under these conditions, soils are therefore more prone to structural breakdown due to slaking and dispersion, the latter is exacerbated by the mechanical rainfall impact which is expected to increase with increasing intensity in rain storms. Furthermore, as a result of climate change, there will be also higher incidence of tilling the soil at inappropriate soil water content, resulting in compaction and smearing (when too wet) and pulverization (when too dry). The actual impact on structure under predicted climate change will be dependent on soil types, particularly as discussed above, on their vulnerability. Under climate changes, higher incidences of fire and flooding are also expected. Fire usually reduces soil aggregate stability and can induce, enhance or destroy water repellency depending on the temperature reached and its duration. Reduction in aggregate stability is caused by the removal of soil organic matter and fine root mat. These changes have implications for infiltration, overland flow and rain splash detachment. Reduced infiltration is often observed in burnt area relative to un-burnt area due to induced water repellency and sealing of pores due to collapse of soil surface aggregates. On the other hand, fire (> 270 ºC) can remove water repellence and increase infiltration of hydrophobic soils (***Chan, 2011***).

II. *Indirect impacts of climate changes on soil structure:*

Climate changes can impact soil structure indirectly via possible effects on soil biology. With the different environmental changes associated with climate changes, direct and indirect changes on soil biology can occur. Soil organisms, particularly the "***soil engineers***", namely ***earthworm and termites***, can have profound effects on soil structure and associated soil physical properties such as hydraulic conductivity. Earthworm and termite activities affect soil structure through: (1) the selective ingestion of mineral and organic particles; (2) their egestion as faecal pellets and organo-mineral aggregates; (3) digestion processes that may modify the colloidal properties of organic matter; and (4) building of long-lasting galleries, burrows and chambers. Absence of these macro-engineers results in strong profile differentiation because of the lack of mixing activities. The dominant role of the burrows (macro-pores) created by earthworms in controlling hydraulic properties of soil has been reported by many (e.g. ***Chan 2004***; ***Chan and Heenan 1993***).

Chan (2004) reported that the infiltration rate of one single burrow created by an Australian anecic earthworm (*Anisochaeta chani*) was equivalent to 1.9 times that via the rest of soil matrix over 1 m^2 area, and there were 157 m^{-2} of these burrows present in the soil under pastures. Loss or reduction in the population of these earthworms with resulting reduction in these transmitting macropores can therefore have important consequences on the hydrology of the soils. Loss of continuous earthworm channels was the cause of the increased runoff and soil erosion observed in the adjacent cropping soils. The potential impact of earthworm on soil structure and plant productivity can also be estimated from previous research on earthworm introduction. The improved soil structure and soil–water relationship observed as a result of earthworm introduction were responsible for the observed increased root growth and pasture yield (***Chan, 2004***).

The expected changes in temperature will expand the latitudinal distribution of termites and favor humivorous termites and endogeic earthworm species that feed in the soil. Invasion by peregrine exotic species can have dramatic effects on soil structure and the associated soil functions. This is well demonstrated in the case of forest clearing in Brazil (***Barros et al. 2004***). Soil structural degradation occurred in the pasture soils after forest clearing and the resulting reduction in soil macro-faunal diversity. Invasion of degraded pasture by earthworm *Pontoscolex corethrurus* in Brazilian Amazonia resulted in significant soil compaction (reduction in total porosity by 20–30%) resulting in reduction in infiltration (***Barros et al. 2004***).

Indirect effect of climate change on soil organisms occurs via changes in both the quantity and quality of food source (litter). Yield reduction of agricultural crops has been predicted for large parts of the world, particularly those under rain-fed situation, and this will result in less cover and input of soil ecosystems. Both of the latter can affect soil structural stability and soil biology. In some African countries, yield from rain-fed agriculture could be reduced by up to 50% by 2020, and in southern and eastern Australia, production is projected to decline by 2030 (***IPCC, 2007a; Chan, 2011***).

Finally, direct and indirect impacts of climate changes on soil biology can result in profound changes in soil structure. However, the extent of soil structural changes will be dependent on the soil organisms, the magnitude of climate changes and location/soil specific. Improved understanding of the impact will require further monitoring and research (**Table 3.6**).

Table 3.6: Examples of improved water use efficiency and crop yield increases due to soil structural improvement (adapted from ***Chan, 2011***)

Method	*Soil structural improvements*	*Soil water changes*	*Crop and yield improvements*	*Ref.*
Gypsum	Better infiltration	Improved water availability	20–50% increases in wheat yield	(1)
Gypsum	Improved hydraulic conductivity, improved drainage	137% increased soil water storage to 1.2 m depth	Better establishment, tiller production and less disease Up to 230% increase in wheat yield	(2)
Gypsum	Increased hydraulic conductivity	Increased water entry; higher subsoil water	Doubled WUE of pastures	(3)
Conservation tillage	Higher macroporosity, structural stability and infiltration, higher soil carbon	Increased plant available water	28% higher soybean yield than conventional tillage	(4)
Conservation tillage	Higher hydraulic conductivity, improved aggregate stability and higher organic carbon	Increased soil water storage, increased WUE	18% wheat and 20% pea yield than conventional	(5)
Conservation tillage	Higher infiltration rate; higher organic carbon; higher earthworm activity	Higher WUE	Mean grain yield over 21 seasons was 15% higher	(6)
Conservation agriculture	Higher infiltration; reduced draught	Higher WUE	Yield increases from 20 to 120% in East Africa	(7)

References: (1) Howell (1987); (2) McKenzie and So (1989); (3) Bridge and Tunny (1982); (4) So et al. (2008); (5) Zhang et al. (2008); (6) Lal (1982); (7) Wani et al. (2007).

3.1.4 *The Effects of Climate Changes on Soil pH*

There is no doubt that variable and changing climate will impact on soil pH and thus indirectly on a myriad of biogeochemical and physical processes occurring in the soil–water–microbe–plant continuum in native and managed terrestrial and aquatic ecosystems. However, such impacts would be dependent on soil type and environmental factors. Further work in discerning the effects of increasing air and soil temperatures as well as changes in rainfall distribution and intensity (getting either wetter or drier) on soil pH and other properties is urgently needed. Such knowledge will underpin management decisions required to protect soils as one of the most precious natural resources.

In areas where climate is expected to become warmer and wetter, microbial activity may increase, resulting in increased soil air CO_2 concentrations as well as higher leaching of basic cations due to increased rainfall. Enhanced cation leaching will initially increase stream alkalinity at the expense of reducing base saturation levels on the soil exchange sites. With time, however, such scenario is likely to result in increased soil acidity, reduced input of alkalinity into surface waters and eventually acidification of these waters (***Welsch et al. 2006***).

In different parts of the world, variable and changing climate will result in either increased or decreased rainfall accompanied by increased temperatures. As mentioned above, increased precipitation will result in enhanced leaching of basic cations, which can exacerbate soil acidification. Greater acidification will require larger amounts of lime for amelioration of soil acidity, but there are significant spatial, transportation and other financial issues associated with lime application, especially in extensive agricultural systems. Absence of adequate liming will result in soils acidifying to a point of becoming unproductive and, moreover, uneconomic to be brought back into production (***Rengel, 2011***).

Greater soil acidification may also arise due to greater biomass production (caused by increased temperatures and increased CO_2 partial pressure in the air). It should be borne in mind that most plant material contains excess cations to balance negative charges on organic molecules (H^+ was exuded into the soil in exchange for nutrient cations). If such plant material gets decomposed in situ, alkalinity accumulated in the plant material is returned to soil, thus neutralizing soil acidity. However, in managed ecosystems that produce food, feed and fibre for economic benefit, a large proportion of the biomass produced is harvested and removed from the site (hence, biomass containing alkalinity is removed, leaving non-neutralized acidity in soil – this represents unbalanced C cycle). Regarding the N cycle, when plant material is produced and decomposed in situ (balanced N cycle), there are two equivalents of H^+ produced in soil (in nitrification) and two equivalents consumed (one during nitrate uptake and the other in converting ammonia to ammonium). If nitrate produced in decomposition of organic matter is leached, one equivalent of H^+ is not consumed in soil (i.e. absence of nitrate uptake), thus leaving non-neutralized acidity in soil (unbalanced N cycle). In scenarios of variable and changing climate that will result in increased biomass production in agricultural and forest systems due to increased temperature and/or rainfall, the harvest and removal of that increased biomass will result in increased removal of alkalinity from such systems as well as in unbalanced C and N cycles. On the other side, increased partial pressure of CO_2 in the soil air, though, is unlikely to have an effect on soil pH on its own (because H_2CO_3 is a weak acid) (***Rengel, 2011***).

The interactions driven by climate change and influencing terrestrial ecosystems (soils, water, plants, animals, microbes) are complex and interdependent. For example, climate change altered the species composition of forest (***Kotroczo et al. 2008***), and decreased the total leaf litter production, which would influence structure and function of microbial communities (a rise in average soil temperature by 2ºC would result in an increase in soil respiration by 22%). Increased tree growth, enhanced soil acidification and a decrease in the C/N ratio in soils accompanied an upward shift of vegetation along the slopes in France due to an increase in CO_2 concentration and increased temperatures. In many parts of the world (e.g. south-west of Western Australia), climate change is expected to result in the climate getting hotter and drier. Such changes may alter N and C cycling processes in soils and result in soil acidification and consequent changes in plant, animal and microbial community structures. However, **Smith et al. (2002)** used an elevation gradient as an analogue of climate change to analyze climatic influence on soil microbial activity and soil properties, concluding that a predicted increase in temperature and decrease in precipitation over the next 100 years would eventually cause the soil pH to increase and the soil electrical conductivity to decrease. This would be accompanied by a decreased nitrification potential and an increase in ammonium concentration. However, an increase in NO_3 leaching with consequent acidification of the surface water was predicted as a consequence of climate change affecting N cycling in soils in a small forested catchment in southern Finland (***Forsius et al. 1997***).

3.1.5 *Climate Changes and Soil Organic Matter*

It is established that, soil organic matter (SOM) is essential in maintaining physical, chemical and biological functions in soil. In fact, SOM is the key indicator of soil health. It contains both living and non-living components. Living components include soil microbial biomass and living roots. Non-living SOM is a heterogeneous organic matter, variously described as labile, slow and recalcitrant SOM, light fraction (free or occluded) and heavy fraction, particulate (> 53 mm) and non-particulate SOM. It is also described by its chemical constituents such as proteins, lipids, starch, carbohydrates, hemicelluloses, celluloses, lignins, polyphenols, pectins and tannins or by humic acid, fulvic acid and humins. Soil organic carbon (SOC) constitutes about 50% of SOM (***Pribyl, 2010***) and contains labile, slow and recalcitrant C pools (***Dalal and Chan, 2001***).

Global climate change scenarios considered are IPCC projection of global temperature increase of 1.6–6.4 ºC by 2100, atmospheric CO_2 concentration increase of up to 550 ppm and precipitation change by at least 20% (***Denman et al. 2007***). It could be also considered that, the influence of atmospheric N deposition, an important component of global environmental change; the rates of N deposition have increased by threefold to fivefold over the past century (***Janssens et al. 2010***) and may continue to increase rapidly in densely populated areas. The increasing rates of atmospheric N deposition may play a major role in modulating climate change impacts (***Dalal et al. 2011***).

SOM is among the best indicator of soil health since it controls many soil properties (***Dalal et al. 2004***) and major biogeochemical cycles including C, N, S and P cycling, and is usually a strong indicator of soil fertility and land degradation (***Manlay et al. 2007***). It also provides the basis for ecosystem services such as through C sequestration, production of food and maintenance of water quality, by serving as an energy source for soil organisms, enhancing pesticide degradation, and by contributing to retention of nutrient ion in coarse-textured and low-activity clay soils. Furthermore, since SOC pool is three times larger than that in the atmosphere (***Denman et al. 2007***), any change in SOC pool due to climate change will have an effect on soil health. Hence, appropriate SOM management is essential for maintaining or improving soil health in the context of climate change (***Dalal et al. 2011***).

It has been well documented that SOC can increase under a range of improved management practices (***Lal et al. 2007***), and the rates of SOC sequestration under a range of land use and management practices have been documented. **Table 3.7** summarizes the rates of C sequestration under a range of management practices and land use. These management practices can be divided into a number of categories, namely crop management including conservation tillage, pasture management, use of organic amendments and land use conversion. It is worthwhile noting that for any specific practice, a range of SOC sequestration rates have been reported (**Table 3.7**). This is expected in view of the factors involved in controlling the production and decomposition of SOM. As many of these management practices were developed for other purpose, such as for soil health improvement, a better understanding of the processes involved in controlling SOC fluxes under these management practices will help to quantify their soil C sequestration potential (***Dalal et al. 2011***).

3.1.6 *Soil Respiration in a Changing World*

It is well documented that, soil respiration is a critical ecosystem process that regulates C cycling and climate in the earth system (***Luo and Zhou 2006***). It could be defined soil respiration as carbon dioxide (CO_2) released from soil to the atmosphere via the combined activity of (1) roots (root respiration) and associated micro-organisms, mainly respiring the recently assimilated C by plants (rhizomicrobial respiration), and (2) micro- and macro-organisms decomposing litter and organic matter (humus) in soil, referred to as “true” heterotrophic respiration (**Figure 3.5**). Soil respiration is usually monitored in situ using classical dynamic or static chamber methodology to measure CO_2 efflux at the soil surface (***Luo and Zhou 2006***). After gross primary production (total C fixed by plant photosynthesis), soil respiration is the second largest C flux in most terrestrial ecosystems and may account for ~70% of total ecosystem respiration on an annual basis. Globally, soil respiration emits 98 ± 12 Pg CO_2-C year $^{-1}$ to the atmosphere, which is approximately an order of magnitude larger than the current annual anthropogenic CO_2-C emissions from fossil fuel combustion (***Boden et al. 2010***). However, despite its global significance, we have only a limited understanding of the magnitude and responses of soil respiration, and especially of its components, to abiotic (temperature, moisture, soil fertility) and biotic (photosynthesis, seasonality of belowground C allocation patterns and root growth, quality and quantity of above and belowground litter) controls. Furthermore, soil respiration is generally greater (~20%) in grasslands than forest stands, and lower (~10%) in coniferous forests than adjacent broad-leaved forests, under similar edaphic and climatic conditions, demonstrating that vegetation type may modulate the influences of abiotic and biotic controls on soil respiration (**Figure 3.6; *Singh et al. 2011***).

Table 3.7: Reported soil organic carbon (SOC) sequestration rates associated with management practices and land use practices that can increase SOC (adapted from ***Dalal et al. 2011***)

Management category	Management practices	C sequestration rates (t C ha^{-1} year^{-1})	References
Crop management	Soil fertility enhancement	0.05–0.15	Lal et al. (2003)
	Better rotation	0.10–0.30	
	Irrigation	0.05–0.15	
	Fallow elimination	0.10–0.30	
Conservation tillage	Stubble retention		Lal et al. (2003)
	Reduced tillage	0.24–0.40	
	No-tillage		
Pasture management	Fertilizer management	0.30	Conant et al. (2001)
	Grazing management	0.35	
	Earthworm introduction	2.35	
	Irrigation	0.11	
	Improved grass species	3.04	
	Introduction of legumes	0.75	
	Sown pasture	0.26–0.72	Chan et al. (2010)
Organic amendments	Animal manure	0.1–0.6	Jarecki and Lal (2003)
	Biosolids	1.0	Brown and Leonard (2004)
Land conversion	Degraded cropland to pasture	0.8–1.1	Grogan & Matthews (2001)
	Bioenergy crop	0.98	

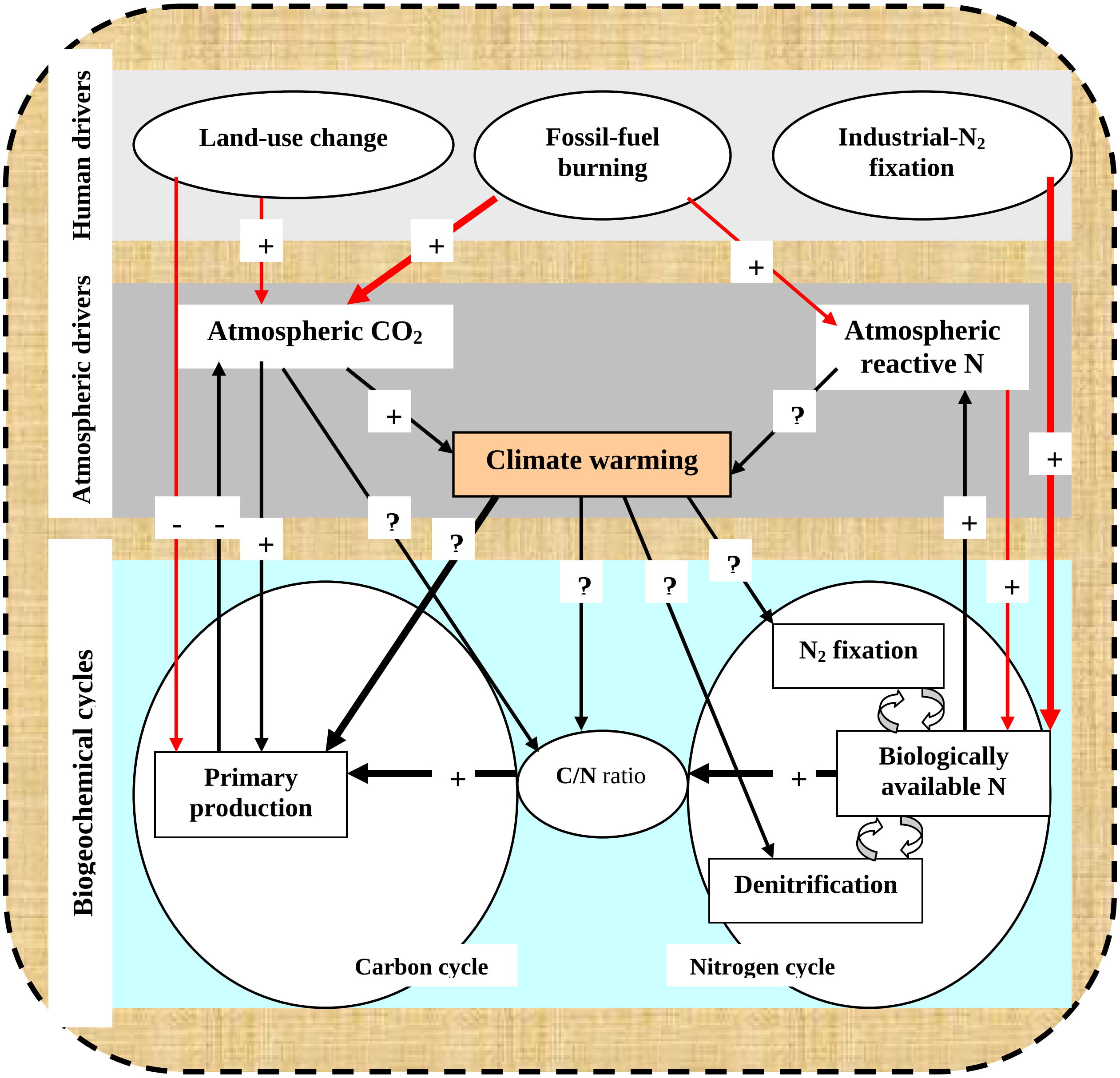


Figure 3.5: Potential nitrogen–carbon-climate interactions. The main anthropogenic drivers of these interactions during the twenty-first century are shown. **Plus signs** indicate that the interaction increases the amount of the factor shown; **minus signs** indicate a decrease; **question marks** indicate an unknown impact (or, when next to a plus or minus sign, they indicate a high degree of uncertainty). **Arrow thickness** denotes strength of interaction. Only selected interactions are shown (adapted from ***Gruber and Galloway, 2008***)

It is well known that, soil respiration is one of the important measures of soil health, because it reflects the capacity of soil to support life (micro- and macro-organisms and plant roots) and is directly related to other functions, such as organic matter decomposition, nutrient mineralization–immobilization and microbial activity in general. Fast rates of soil respiration are indicative of intense biological activity in soil with consequences for plant growth and the environment, e.g. through increased rate of nutrient cycling in soil. Slow rates may indicate little or suppressed biological activity, which may be due to management-induced stresses and/or climate perturbations, or limitations of the resources (such as substrates, nutrients, O_2) required for such biological activity. Soil respiration usually increases following cultivation of lands as a result of increased accessibility of previously protected organic matter within soil aggregates to soil micro-organisms, and this may adversely affect soil C balance. On the other hand, land use and management practices such as conservation tillage, manure and crop residue application, and perennial and deep-rooted crops, which increase organic matter input to soil, may also increase the rate of soil respiration, especially under non-limiting environmental (soil moisture and temperature) conditions. In anaerobic environments, incomplete turnover of soil organic matter may reduce CO_2 emissions, but increase emissions of non-CO_2 greenhouse gases, such as nitrous oxide and methane. Clearly, there are instances where soil respiration may not be a good indicator of changes in net greenhouse gas emissions from soil, and even overall soil health (***Singh et al. 2011***).

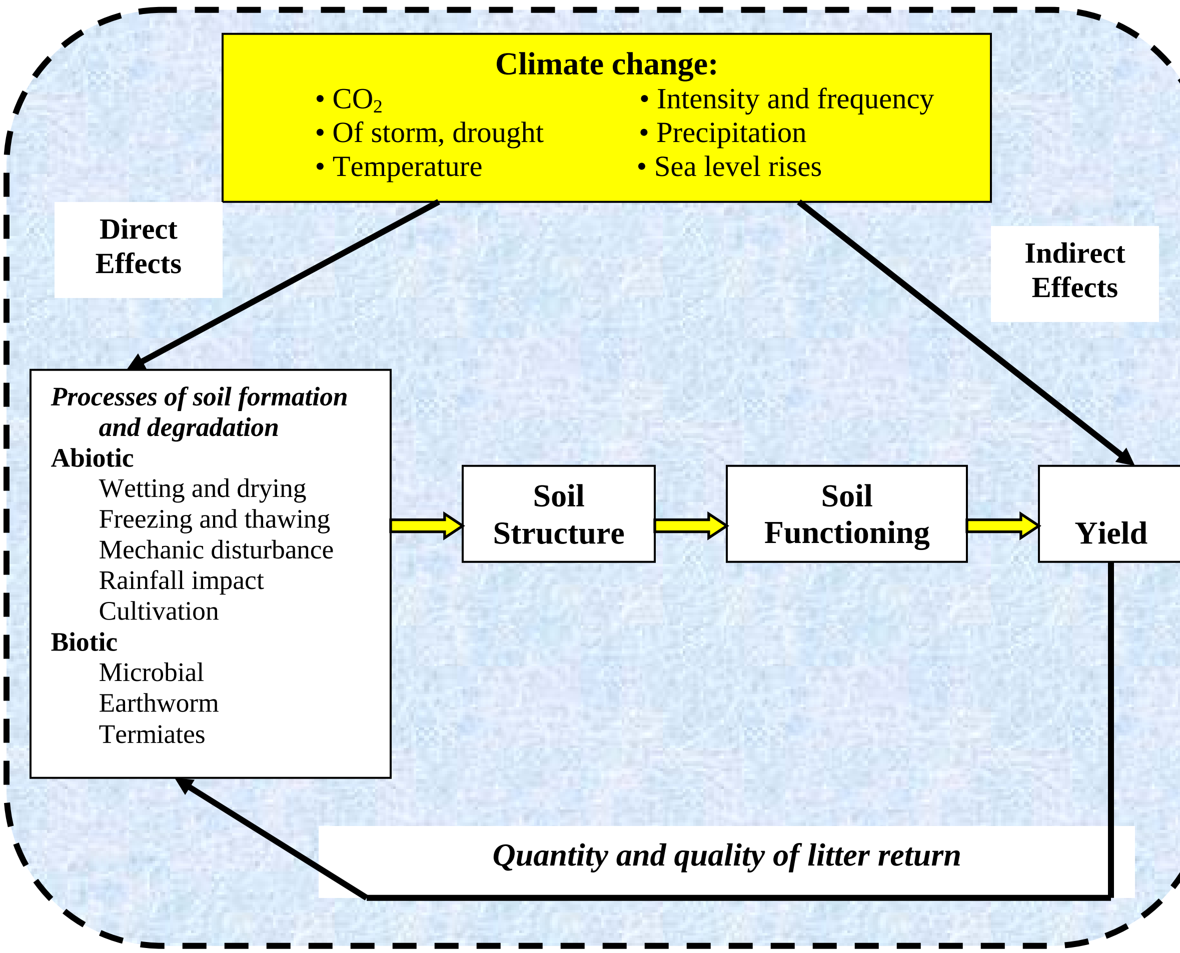


Figure 3.6: The basic relationships between soil structure and crop yield under climate change scenarios (adapted from ***Chan, 2011***)

Such global changes have consequences for the functioning of terrestrial ecosystems, including soil respiration (**Figures 3.7 and 3.8**), and a greater understanding of their interactive effects is required to accurately estimate uncertainties in global climate change projections and predict ecosystem feedbacks to atmospheric CO_2 levels (***Rustad, 2008***). Terrestrial ecosystems are expected to experience multiple, concurrent and interacting changes in global climate, and these global changes will directly or indirectly influence soil respiration via a series of closely interrelated processes and factors affecting the activities of roots and microbes in soil. There are still very few studies that have included multi-factor analysis of soil respiration (e.g. ***Deng et al. 2010***). The available information shows that responses of soil respiration to multiple factors can be non-interactive or interactive and usually non-additive. For example, interactive effects of multiple global change factors were non-significant for soil respiration between warming and increased precipitation, elevated atmospheric [CO_2] and warming, elevated atmospheric [CO_2] and N addition, and elevated [CO_2], air warming and water availability. On the other hand, **Deng et al. (2010)** found a strong interactive effect of elevated atmospheric [CO_2] and added N on soil respiration in young, subtropical forests, and the combined effect of this two-factor treatment on soil respiration was greater (increased by 50%) than either of the treatments alone (29% increase by elevated [CO_2] and 8% increase by N addition). Similarly, belowground C turnover was affected more by warming plus elevated [CO_2] than by elevated [CO_2] alone, and the interaction was strongly mediated by N supply (***Singh et al. 2011***).

While responses of soil respiration to individual regulatory drivers have been studied widely, there is still no clear consensus as to those responses under scenarios of multiple changes in global environment. A lack of consensus and inconsistencies among studies are mainly due to variations in the type and age of ecosystem studied, the timescale of measured responses, artifacts induced by methodologies used (especially when seeking to partition soil respiratory components) or to the size of experimental units (e.g. glasshouse, whole-plant chambers, ecosystem-scale as in free-air carbon dioxide enrichment experiments), and lack of consideration of the confounding influences of other factors not included in experimental designs. There is a clear need for studies considering multi-factor approaches, together with appropriate partitioning techniques and modelling efforts, to disentangle complex responses of soil respiration to global change scenarios and assist in improving climate change projections (***Luo et al. 2008***).

3.1.7 *Impacts of Global Changes on Soil Biota*

The soil biota is linked to the soil health concept through its role in the mediation of processes that provide agricultural goods (e.g. nutrients and disease control for food and fibre production) and ecosystem services (water quality and supply, erosion control, atmospheric composition and climate regulation, pollutant attenuation and degradation, non-agricultural pest and disease control and biodiversity conservation). Therefore, it is imperative when addressing issues of global change impacts on soil health to consider the trilogy of interrelated properties: the physical, chemical and the biological (***Kibblewhite et al. 2008***).

The soil biota remains the most elusive and challenging component of soil health in terms of precise measurement of who is present and active and meaningful interpretation of global change impacts. Several challenges will be highlighted related to: (1) community structure (who is there) to function (what they are doing), (2) microhabitat diversity and scale and (3) applying ecological rules. Soil biota has many and varied roles in all global change. It has a direct causal role, it can also contribute to mitigation and can be changed (either adversely of beneficially) by global change. Both the causal and mitigation roles relate to the capacity of microbes such as bacteria, archaea and fungi to produce and consume all the greenhouse gases, NO, N_2O, CH_4 and CO_2, respectively. In other words, these gases are both starting substrates and by-products of energy-generating pathways necessary for microbial growth and integral to fundamental biogeochemical cycles and a whole range of ecosystem goods and services (***Kibblewhite et al. 2008***).

These processes are cyclic, dynamic and adaptive and are regulated by temperature (ambient and soil), moisture availability, soil and plant management. The soil biota is likely to be affected directly (e.g. physiological stress and adaptation responses) and indirectly (e.g. through habitat modification) by global change scenarios.

These scenarios include the following items:

(1) ***Elevated temperature***: projected increase from 1990 of 1.4–5.8 ºC by 2100.

(2) ***Elevated atmospheric*** $\mathbf{CO_2}$: projected increase from 368 ppm in 2000, to between 540 and 970 ppm by 2100.

(3) ***Elevated atmospheric N***: projected increase of N_2O from 316 ppb in 2000.

(4) ***Fluctuating*** $\mathbf{CH_4}$ ***concentrations*****:** e.g. a rapid rise from about 700 ppb in 1,750 to about 1,775 ppb in 2005, followed by a projected decline.

(5) ***Precipitation changes*** by an average of 20% on current levels (***Solomon et al. 2007***).

Soil biota can also provide solutions for mitigation and adaptation to global change. An example of this is where sensitive species can be used to predict impending biogeochemical changes or where new species can displace existing species to reduce loss of greenhouse gases to the atmosphere (***Mele, 2011***).

Chapin et al. (2009) reported that soil biota is a critical element in the search for new knowledge leading to improved prediction and management of adverse impacts of global change. There are outstanding needs and challenges that must take account of three key facts: (1) soil is the most diverse ecosystem on the planet, (2) only 1%of the soils microbial diversity is catalogued and (3) ecological concepts that apply to aboveground plant communities do not always apply belowground.

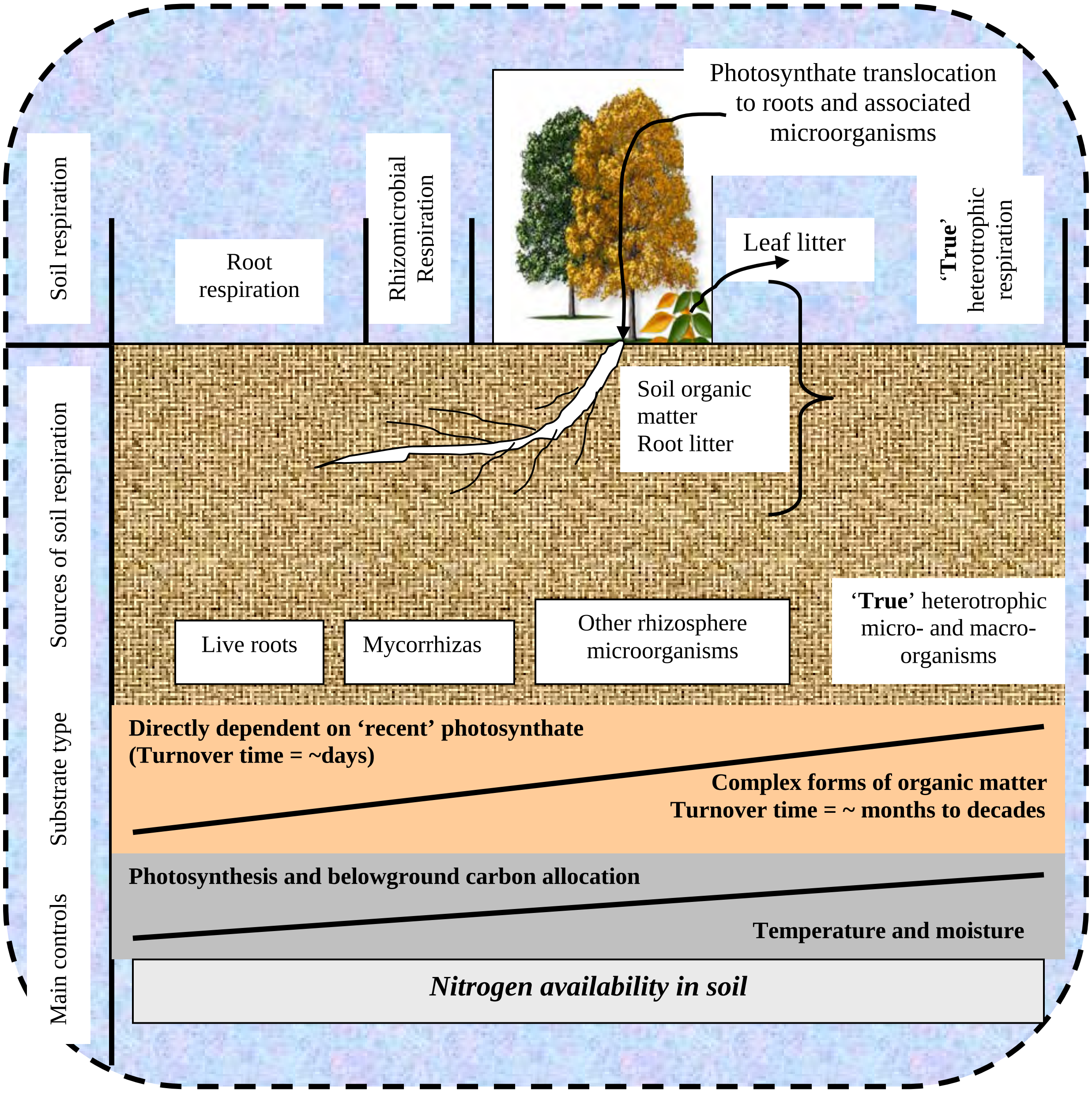


Figure 3.7: Soil respiratory components, autotrophic (root, rhizomicrobial) and "true" heterotrophic respiration, arranged according to their dependency on substrate type (with their turnover times ranging from days for recent photosynthates to months to decades for complex forms of organic matter in soil), belowground carbon allocation supply and environmental controls (soil temperature and water availability). Nitrogen availability in soil may equally influence both autotrophic and heterotrophic components of soil respiration (from ***Singh et al. 2011***)

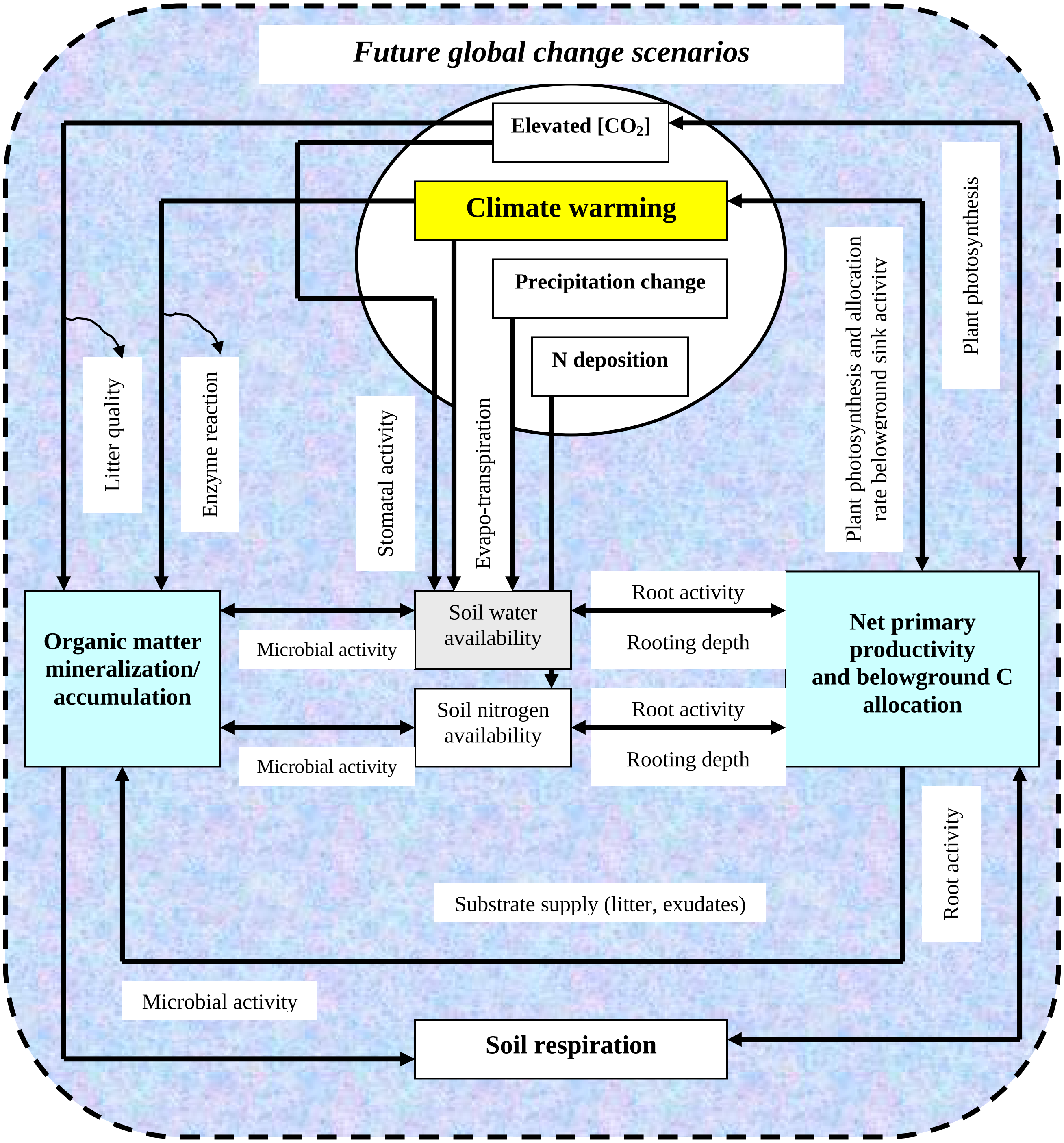


Figure 3.8: Schematic of direct or indirect influences of future global change scenarios on soil respiration via a series of closely interrelated processes and factors affecting the activities of roots and microbes in soil (from ***Singh et al. 2011***)

3.2.8 *Soil Degradation and Climate Changes*

Several natural processes affect the earth's climate, including its orbit around the sun, solar radiation, volcanic activities and their associated emissions, and meteorites. When a meteorite struck the Yucatan Peninsula 65 million years ago, it caused a drastic change in climate and subsequent mass extinction. The greenhouse effect is also a natural process. It has made the Earth inhabitable by raising its temperature from a frigid −18°C to a tolerable 15°C. The greenhouse effect is caused by the presence of various trace gases in the Earth's atmosphere, notably carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). They act as a glass does in a greenhouse— they permit shortwave radiation to enter Earth's atmosphere but impede the outward flow of infrared or long wave radiation, which causes a positive radiation balance; hence, the reference to "greenhouse gases" (GHGs). Because of this imbalance in radiation, the Earth — including its atmosphere and ocean — are warmer by about 33°C than they would be in the absence of this natural greenhouse effect. It is an extreme natural greenhouse effect that has caused the extremely high temperatures on Venus and extremely low temperatures on Mars. In contrast, the Earth's present temperature (15°C) is just right to support an incredible diversity of life. Global warming is caused by acceleration of the natural greenhouse effect because of anthropogenic activities that enrich the atmospheric concentration of GHGs (***Lal, 2005***).

Projected change in climate may influence several soil processes with a consequent adverse impact on soil quality. Important among these processes with an attendant adverse impact on soil quality are:

- Hydrolysis: the leaching of silica and basic cations.
- Cheluviation: removal of Al and Fe by chelating organic acids.
- Ferrolysis: transformation of clay by alternating oxidation and reduction processes, and reduction in cation exchange capacity.
- Dissolution: of clay minerals by strong acids producing acid aluminum salts and amorphous silica.
- Clay formation: reverse weathering leading to clay formation and transformation.

Hydrolysis and cheluviation may accelerate with temperature increases, and ferrolysis may occur in soils subject to reduction and oxidation in high latitudes and monsoonal climates. These processes increase soil erodibility and decrease water and nutrient-retention capacity. Accelerated soil erosion and other degrading processes already affect soil quality, especially in developing countries of the tropics and subtropics (**Table 3.8)**. Soil degradation is likely to be accelerated by projected climate change, especially in ecologically sensitive regions. Global hot spots of soil erosion include the Himalayan–Tibetan ecosystem, the unterraced slopes of China and Southeast Asia, tropical areas of Southeast Nigeria, the semiarid Sahelian region of West Africa, sloping lands of Central America, and the Andean valleys and cerrado region of South America (***Scherr and Yadav,***

1996). Soil erosion rates are likely to change due to the erosive power of rainfall produced by more extreme precipitation events (***Lal, 2005***).

Higher temperatures due to projected climate change, especially in arid and semi-arid regions, may produce higher evaporative demand for water and exacerbate the drought that often follows the plow. If the soil and water are adequate, as with irrigation, it turns out that an increase in evaporative demand may heighten the risks of salinization (***Brinkman and Sombroek, 1996***). However, under high atmospheric CO_2 conditions, there may be increased salt tolerance of crops. Re-vegetation by overgrazing and other factors could exacerbate the problem of desertification, especially in Sub-Saharan Africa. Risks of over extraction of groundwater for irrigation in South Asia and also in the Near East/North Africa region are already recognized as serious. Thus, soil degradation is a major threat to global food security, and this threat may be increased with anticipated climate change. Soil degradation, especially that caused by accelerated erosion, characteristically involves depletion of soil organic matter. Most degraded soils contain an SOC pool that is below their potential set by ecological factors (***Lal, 2005***).

Table 3.8: Soil degradation in developing countries (millions ha) (adapted from ***Lal, 2005***)

Region	Soil Erosion by Water	Soil Erosion by Wind	Chemical Degradation	Physical Degradation
Africa	227	186	62	19
Asia	441	222	74	12
South America	123	42	70	8
Central America	46	5	7	5
World total	1094	548	240	83

3.2 *Water Crisis in a Changing World*

3.2.1 *Introduction*

Changes to the earth's climate have a direct effect on the global hydrological cycle and hence on water. The rise of temperatures may exacerbate existing water shortages, impair water quality or enhance the frequency and intensity of floods and droughts. In particular countries in the transition zone from wet to dry arid climatic conditions have experienced water-related problems, such as uneven distribution of water resources and year-to-year variability. These changes in water resources and water-related extreme events are likely to affect social and economic developments. Water resources are one of the highest-priority issues with respect to climate change impacts and adaptation in the Middle East and North Africa. While many aspects of climate variations and their impact on water resources have been presented and published, the information is still greatly dispersed and lacks a general overview.

3.2.2 *Climate change and global water crisis*

Food policy (the ability of a country to supply an assured access to food – in an adequate quantity and quality to meet basic food demands by all social groups and individuals at all times ***Barrett, 2010***) must not lose sight of surging water scarcity. Water is a key driver of agricultural production. Water scarcity can cut production and adversely impact food security. Irrigation has helped boost agricultural yields and outputs in semi-arid and even arid environments and stabilized food production and prices (***Hanjra et al. 2009a, 2009b***) and the revenue from the agriculture sector (***Sampath, 1992***). Only 19 % of agricultural land cultivated through irrigation supplies 40% of the world's food (***Molden et al. 2010***) and has thus brought substantial socioeconomic gains (***Evenson and Gollin, 2003***). Water for agriculture is critical for future global food security. However, continued increase in demand for water by non-agricultural uses, such as urban and industrial uses and greater concerns for environmental quality have put irrigation water demand under greater scrutiny and threatened food security. Water scarcity is already a critical concern in parts of the world (***Fedoroff et al. 2010***). Further, there are growing public concerns that the footprints (i.e. negative impacts) of food security on the environment are substantial (***Khan and Hanjra, 2009; Khan et al. 2009a,b***). Continued increase in demand for irrigation water over many years has led to changed water flows, land clearing and therefore deteriorated stream water quality. Addressing these environmental concerns and fulfilling urban and industrial water demand will require diverting water away from irrigation. This will reduce irrigated area and its production and impact on future food security (***Hanjra and Qureshi, 2010***).

The severity of the water crisis has prompted the United Nations (***UNDP, 2007***) in concluding that it is water scarcity, not a lack of arable land, which will be the major constraint to increased food production over the next few decades. For instance, Australia is one of the major food producing and land abundant countries but recent drought reduced its agricultural and food production substantially (***Goesch et al. 2007***). According to 2001 and 2006 land use data by the **ABS (2008)**, in the Murray–Darling Basin (MDB) of Australia, there was a decline of about 40% in rice and cereals production. Drought in other food producing countries such as parts of the United States of America and Europe is regarded as one of the major factors that contributed to the global food price crisis of 2008 (***Piesse and Thirtle, 2009***). Inequitable distribution of available food supplies, poverty, and inequality result in entitlement failure for the poor to exacerbate the food security issues because those lacking water entitlements are often food insecure (***Molden, 2007***). The high and widening inequality and income gap between the rich and the poor is a serious concern; though it is amazing that while one billion people are hungry in the developing world (***Barrett, 2010***), a significant proportion of the population in the developed countries is obese (***Schaefer-Elinder, 2005; Hanjra and Qureshi, 2010***).

Global demand for water has tripled since the 1950s, but the supply of fresh water has been declining (***Gleick, 2003***). Half a billion people live in water-stressed or water-scarce countries, and by 2025 that number will grow to three billion due to an increase in population. Irrigated agriculture is the dominant user of water, accounting for about 80% of global water use (***Molden, 2007***). Population and income growth will increase the demand for irrigation water to meet food production requirements and household and industrial demand. The global population is projected to increase to about 9 billion by 2050. In response to population growth and rising incomes, worldwide cereals and meat demand has been projected to increase by 65% and 56%, respectively (***de Fraiture et al. 2007***). Fulfillment of calorie requirements and dietary trends will translate into even higher water demand if more calories will be supplied from meat (***Rosegrant and Cline, 2003***). At the same time, the limited easily accessible freshwater resources in rivers, lakes and shallow groundwater aquifers are dwindling due to over-exploitation and water quality degradation (***Tilman et al. 2002; Hanjra and Qureshi, 2010***).

Water availability varies by several orders of magnitudes for the different countries in the Middle East and North Africa (MENA) region and so fresh water availability per capita ranges from highly water stressed countries like Jordan (200 m^3 $year^{-1}$ $capita^{-1}$) to less water-stressed counties like Iraq (4,340 m^3 $year^{-1}$ per capita; **Table 3.9**). Countries with surplus water supply are based on surface water flows (Iraq, Syria, Lebanon, Egypt, Sudan), whereas groundwater-based countries have significantly higher water stress at present. For instance, the most populous Arab state, Egypt, is comparably well endowed with renewable water resources, since it receives 96% of its water resources from the Nile River. In contrast, the Arabian Peninsula and North Africa (with the exception of Morocco) have more limited flows of renewable water, and typically draw on 'fossil' (nonrenewable) aquifers to meet current demands. Given its relatively large and growing population, however, in per capita terms aggregate water supply in Egypt will become increasingly constrained (estimated 590 m^3 $year^{-1}$ $capita^{-1}$ in 2025) compared with Iraq (2,200 m^3 $year^{-1}$ $capita^{-1}$). Assuming no change in water availability, expected population growth for 2025 will dramatically increase the water stress in the MENA region, as water availability per capita is expected to decrease in the range of 30% to 70% (an average of 42%; ***Sowers et al. 2010***).

The expected increase in water stress (defined here as less than 500 m^3 $year^{-1}$ $capita^{-1}$) will affect most countries in the MENA region, but in groundwater-based countries, which already suffer from water stress, population growth will exacerbate the already existing water crisis. In surface water-based countries, the absolute water availability per capita will exceed the threshold of 500 m^3 $year^{-1}$ $capita^{-1}$ that defines water stress (Morocco, Egypt, Sudan, Syria, Lebanon, and

Iraq) in 2025. This is based on the assumption that the river discharge in these countries will not vary significantly from 2000 figures. However, if we take into account the climate change factor, surface water-based countries may experience a dramatic reduction in surface flow, if global warming affects precipitation in intake areas of their rivers. Consequently, while population growth is expected to affect all countries in MENA region, climate change could have a greater affect on countries in which water supply is based on surface water (***Sowers et al. 2010***).

Table 3.9: Water resource indicators: Total freshwater resources, available resources, use, and water availability in selected Mediterranean countries **(**adapted from ***FAO, 2005; Iglesias et al. 2007; Sowers et al. 2010***)

Country	Rainfall (mm yr^{-1})	IUWR	UWR	IGW	TWU1	TWU2	PTUWR	WAPC	
								2000	**2025**
Algeria	89	13.90	14.32	1.70	5.74	40	473	111	75
Egypt	51	1.80	58.30	1.30	61.70	106	859	49.1	42.1
France	867	178.50	203.70	100.00	35.63	17	3,439	---	---
Greece	652	58.00	74.25	10.30	7.99	11	6,998	---	---
Italy	832	182.50	191.30	43.00	43.04	22	3,325	---	---
Libya	56	0.60	0.60	0.50	5.73	954	113	253	108
Morocco	346	29.00	29.00	10.00	12.23	42	971	299	164
Spain	636	111.20	111.50	29.90	35.90	32	2,794	----	---
Syria	252	7	26.26	4.2	20.6	100	1,403	1170	1010
Tunisia	313	4.15	4.56	1.45	2.58	57	482	132	81.5

Data of (2004) IGW= Internal Ground water (km^3 yr^{-1})
IUWR= Internal usable water resources (km^3 yr^{-1}) UWR= Usable water resources (km^3 yr^{-1})
PTUWR= Potential total usable water resources (m^3 $capita^{-1}$ yr^{-1})
WAPC= Water availability per capita (m^3 $year^{-1}$ $person^{-1}$)
TWU1= Total water use (km^3 yr^{-1}) TWU2= Total water use (% renewable)

3.2.3 *Global climate changes –sources and impacts on the water cycle*

The global water cycle links climate and hydrology and plays a critical role in the climate system. The perception that humans are responsible for an inevitable change in the climate is gaining widespread acceptance. In particular, the most recent report of the Intergovernmental Panel on Climate Change (IPCC) affirms that climate change is already taking place and that its main cause involves human activities. Although the spectre of climate change is leading to many concerns about human livelihoods and ecosystem sustainability, nowhere are such concerns greater than those related to the impacts of this change on freshwater resources and their implications for society. Water-cycle scientists are considering the implications of climate change for the water cycle by addressing large-scale questions such as ‘Is the global water cycle accelerating or intensifying?’, as well as questions about local and watershed scale impacts. Water plays a critical role in the welfare of societies around the world and affects the livelihood of every human. It is essential for the maintenance of life. Virtually all living fauna and flora consist of a significant proportion of water and must maintain those proportions for life to continue. More generally, water is an essential input that strongly affects the productivity and success of a number of economic sectors, from agriculture to energy production. It is also a means of transportation and a source of clean energy. In short, the survival of every human, every region, and every society depends on having access to a share of the world's water through the global water cycle (***Grafton and Hussey, 2011***).

The Earth's climate has changed many times during the planet's history, with events ranging from ice ages to long periods of warmth. During the last centuries natural factors such as volcanic eruptions or the amount of energy released from the sun have affected the Earth's climate on a smaller scale. Beginning since the 19^{th} century, due to human activities associated with emissions of CO_2 and other greenhouse gases the composition of the atmosphere has changed. The scientific community has reached consensus that this changes cause a warming of the atmosphere and therefore influencing the Earth's climate. Continuation of greenhouse gas emissions can result in additional warming over the 21^{st} century up to 4.5 °C by 2100. This warming will have severe consequences for the water cycle of the world, because with the warming will come changes in precipitation patterns with increased risk of droughts and floods.

The assessment of the influences of climate changes on the global hydrological regimes and water resources are still very uncertain due primarily to the complex meshing systems as well as to an inadequate understanding of the water cycle in the oceans, atmosphere and biosphere. For assessing the effects water-balance calculations are necessary, including temporal and spatial changes in the relevant hydrologic parameters. Empirical knowledge would have to be replaced increasingly by improved process understanding. Overcoming this problem requires new ways in a field traditionally divided amongst several disciplines. In order to improve the assessment general circulation models are applied nowadays to simulate climate-change scenario and to evaluate possible future changes. Although there is variation between scenarios, the results suggest that average annual runoff will increase in high latitudes and in the equatorial regions, but will decrease in mid-latitudes and most subtropical regions. The selected scenario produces changes in runoff which are often closely related to the initial conditions, but there are important regional differences. The study also showed that different indications of the impact of climate change on water resource stresses could be obtained using different projections of future water use (***Zereini and Hoetzl, 2008***).

One of the major impacts of global warming is likely to be on hydrology and water resources, which in turn will have a significant impact across many sectors of the economy, society, and environment (**Figure 3.9**). Characteristics of many ecosystems are heavily influenced by water availability. Water is fundamental for human life and many activities, including agriculture, industry, and power generation. On the global scale, climate change is likely to worsen water resource stress in some regions but perhaps ameliorate stress in others. At the regional scale there are mixed signals. A major impact of climate change over the African continent is a shift in the temporal and spatial distribution of precipitation. This will result in a shift of runoff or hydrological resources in both time and space. Future climatic changes in the Nile River basin would be significant and possibly severe. For example, with 4°C warming and a 20 percent decrease in precipitation, Nile River flow decreases 98 percent. This represents a significant reduction in water supply (***Gleick, 1998***). Based on the results of the river flow responses, climate variables alone can cause a 50 percent change in runoff in the Gambia River catchment. In general, a 1 percent change in rainfall will result in 3 percent change in runoff. For the Zambezi River basin, simulated runoff under climate change is projected to decrease by about 40 percent or more (***Mavi and Tupper, 2004***).

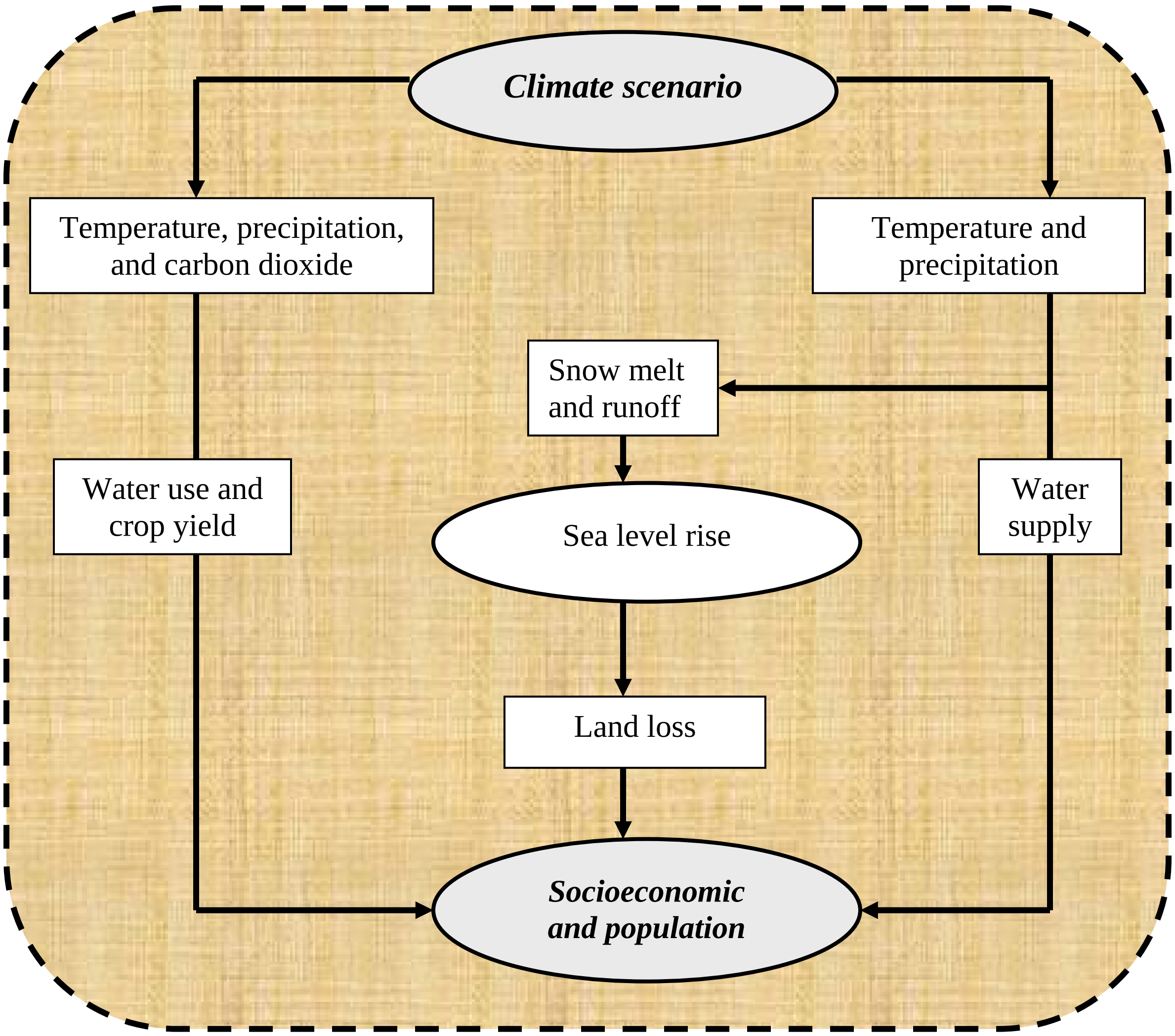


Figure 3.9: Impact of climate change on water resources and agriculture (adapted from ***Mavi and Tupper, 2004***)

Since the 4th Assessment Report of the International Panel on Climate Change (IPCC-4.AR), presented to the public in early spring 2007, there can be no doubt: global climate is changing, at least partly because of human activities. To predict the future climate change expected to occur over the next 100 years highly sophisticated climate models (or rather earth system models) are used. According to these models global warming will be between 1° and 6.3° C in 2100, depending on the scenario. The question arises how reliable all these model predictions are. In fact, the performance of these climate (or earth system) models is highly impressive when modelling the well-documented climate change that occurred over the last 150 years. On the other hand all models have their imperfections. For instance, recent climate models still suffer from insufficient representations of the cloud dynamics, of soil processes or of biosphere-atmosphere interactions. Moreover, all models have to use the technique of parameterization with the inherent problem that these parameterizations are adapted to certain situations and are valid only within specific boundary conditions. Hence, it is to be expected that model predictions for climate states far away from the present-day situation have higher uncertainties. It could be considered four examples, i.e. the effect of global warming on a) seasonality and rainfall, b) on forests and climate feedbacks, c) on the Gulf Stream and European climate, and d) on the arid and semiarid zones. For these four examples the lessons from the past are most relevant for understanding and managing future climate change and are only partly consistent with model results (this is particularly true for examples c and d). Thus they may point out particular weaknesses and uncertainties of model predictions. On the other hand, it is clear that the past can never directly be used as a perfect representation of the future: earth and climate history are indeed historical processes, past situations are never repeated identically in the future (***Mosbrugger, 2008***).

Global climate change is reality. The same holds for anthropogenic forcing as an additional climate factor although some quantitative uncertainties remain. Again it is a fact, that this change has its impact on the global water cycle. The recent **IPCC Report (2007)** expects that much of the ob served climate trends observed so far may continue at least for some decades, broadly independent from mitigation measures due to the inertia effects of the climate system. As late as roughly in the second half of this century, mitigation measures, predominately reductions of GHG emissions may slow down anthropogenic climate change. In the mean time there is no chance than to adopt on unavoidable climate change. For the Mediterranean and North Africa the main challenge is to meet the problems of water stress (aridity) with all its ecological and socio-economic consequences.

Climate varies on all scales of time and space since Earth exists. However, within industrial time, roughly since 100-200 years, mankind has become an additional climate forcing factor of growing intensity although the anthropogenic influence on climate can be traced back several thousands of years due to land-use effects (development of agriculture and pasture), including deforestation. The most important recent effect, however, is the emission of infrared (IR)-active trace gases (greenhouse gases GHG) such as CO_2 and others due to fossil energy use. In consequence, the atmospheric CO_2 concentration has increased from pre-industrial values of approximately 270-280 ppm (nearly constant since the termination of the last ice age c. 10,500 years ago) to more than 380 ppm in 2006. In combination with the concentration increase of some other GHG (CH_4, N_2O, CFCs, tropospheric O_3 etc.) climate model simulations as well as statistical assessments attribute to this GHG forcing an increase of the global mean surface air temperature of approximately 0.7 K within the recent 100 years (***IPCC, 2007***). Other external forcing of the climate system like solar activity and volcanism or internal mechanisms of the climate system like El Niño and other have predominantly produced fluctuations around this long term trend. However, such as this trend is not uniform in time, it is also not uniform in space. There is a marked interacting between the different temperature regimes of the Earth and atmospheric circulation and this interaction may be modified due to global climate change. Moreover, global atmospheric circulation is linked with the global water cycle. Briefly characterized, evaporation and transpiration (from vegetation; combined evapotranspiration) leads to water vapour transport into the atmosphere where in the context of uplift processes, like in case of low atmospheric pressure, clouds are formed and some of these clouds produce precipitation. On average, in case of ocean areas evaporation exceeds precipitation (arid climate) and the surplus of water vapour is transported to land areas where, again on average, precipitation exceeds evapotranspiration (humid climate). In the latter case, the surplus is transported to the ocean by river runoff and groundwater flow. **Table 3.10** presents also the results of related climate model simulations (***Schoenwiese, 2008***)

It should be noted that climate change is not the only influence on water availability and the global water cycle. The availability of water is also affected by:

- Population size and growth, which has a large impact on the demand for water;
- Movement of people from rural environments to urban environments, which leads to shifts in water use patterns;
- Higher demands for food security, which increases the requirement for irrigation water;
- Pollution from industrial and agricultural applications, which affects the quality of water available for domestic and industrial use; and
- Land use changes which affect the local cycling of water.

These topics are dealt with in depth elsewhere in this book but are mentioned here so that climate change influences can be considered in the context of the other anthropogenic factors influencing water availability and use. The remainder of this chapter focuses on the linkages between changes in the climate system and the water cycle, and discusses the consequences of these anticipated changes for the freshwater resources of the Earth (***Lawford, 2011***).

Table 3.10: Evaporation, precipitation and run-off as assessed from observational data and modeled (Max Planck Institute for Meteorology MPIM, Hamburg, coupled atmosphere-ocean circulation model ECHAM4-OPYC, reference period 1990-1999) (adapted from ***Schoenwiese, 2008***)

Author	Evaporation (ocean)	Precipitation (ocean)	Precipitation (land)	Evaporation (land)	Run-off (land)
Baumgartner and Reichel (1975)	425 (1176)	385 (1066)	111 (746)	71 (480)	40 (110)
Trenberth et al. (2006)	413 (1143)	373 (1033)	113 (759)	73 (494)	40 (110)
Model, MPIM, Marcinek (2007)	453 (1253)	411 (1138)	118 (793)	78 (527)	46 (127)

The global water cycle redistributes water from oceans to land through atmospheric circulation and then back to the ocean primarily through surface and sub-surface flows (runoff). Annually, there is a net flux of moisture from the world's oceans to the atmosphere as a result of the excess evaporation over oceans and net flux of water from the air to the land because land precipitation exceeds land evaporation when averaged over the globe. Evaporation, atmospheric moisture transport, and precipitation are key processes and fluxes for the movement of moisture from source to sink regions. Energy to keep the cycle operating is supplied by the sun's heat which creates an equator-to-pole atmospheric pressure differential that maintains the atmospheric circulation and provides the energy required for the phase transitions between the solid, liquid, and gaseous phases (***Lawford, 2011***).

3.2.4 *Impact of climate change on fresh water resources*

Is it really necessary to be considered the importance of water resources? Without water, there would be no life on this planet. Water is *the* major environmental issue of the 21st century; all other concerns pale in comparison. We think of Earth as a water world, and it certainly is, with ocean waters covering nearly 71% of Earth's surface. Ninety - eight percent of the water on the planet is in the oceans and therefore unusable for drinking. Of the 2% of the fresh water, the majority is in glaciers and the polar ice caps. Approximately 0.36% is in underground aquifers, and about the same amount makes up our lakes and rivers. But although there is plenty of water on Earth, it is not always in the right place, and it is not always there when we need it. The world's population is expected to expand to over 9.4 billion people by 2050, and scientists are concerned that our water resources will not be able to already in short supply in many parts of the nation, and the situation is only going to get worse. As the population continues to grow, demands for water increase, and climate change mucks up the hydrologic cycle, water will become even scarcer. Water resources involve surface water, water below ground, and water that falls from the sky. Most cities meet their needs for water by withdrawing it from the nearest river, lakes, reservoir, or aquifer. One thing discovered over the years is that groundwater and surface water are fundamentally interconnected and are integral components of the hydrologic cycle (***Sipes, 2010***).

The importance of water cannot be overstated: it is essential for all life on Earth. So while the world is preoccupied by the threat of climate change, all those involved in the debate understand that when we talk about climate change the subtext is, how will water be managed? When we discuss the need to 'adapt' to climate change, we are, in one aspect, addressing the need to deal with either more, or less, water. At the same time, anyone who has been involved in water resource management will tell you that we have been 'adapting' to our climate ever since the Bronze Age, when humans decided to settle down and establish organised agriculture. Some 4000 years and 7 billion people later, and with all our clever water infrastructure and technology, we are still trying to get it right. As per capita water volumes decrease, water conflicts will be exacerbated. In response to water scarcity, diversions of water from one area or catchment to another are likely to increase. Unfortunately, there are few places left in the world where additional water can be tapped without imposing substantial costs on existing users or on the environment. Moreover, in agricultural terms, a growing world population will place a greater strain on water resources to grow the food to sustain upwards of 2 billion more people. Since agriculture uses some 70% of total freshwater withdrawals, this will place an even greater challenge on food security (***Grafton and Hussey, 2011***).

The availability of fresh water will be substantially changed in a world affected by global warming. Although uncertainties remain for projections of precipitation particularly on the regional or even river-basin scale, it is possible to identify many areas where substantial increases or decreases are likely. For instance, precipitation is expected to increase in high latitudes and in parts of the tropics and decrease in many mid latitude and sub-tropical regions especially in summer. Further, increase of temperature will mean that a higher proportion of the water falling on the Earth's surface will evaporate. In regions with increased precipitation, some or all of the loss due to evaporation may be made up. However, in regions with unchanged or less precipitation, there will be substantially less water available at the surface. The combined effect of less rainfall and more evaporation means less soil moisture available for crop growth and also less run-off – in regions with marginal rainfall this loss of soil moisture can be critical. Although, increased CO_2 also tends to reduce plant transpiration and less water use by plants, a factor that requires further investigation. The run-off in rivers and streams is what is left from the precipitation that falls on the land after some has been taken by evaporation and by transpiration from plants; it is the major part of what is available for human use. The amount of run-off is highly sensitive to changes in climate; even small changes in the amount of precipitation or in the temperature (affecting the amount of evaporation) can have a big influence on it. To illustrate this, **Figure 3.10** shows estimates of the mean change in annual run-off between 1980–2000 and 2081–2100 under the SRES A1B scenario. There are changes of up to plus 50% or minus 50% in many places. Water availability in many locations and watersheds will change a great deal as the century progresses. Note that Figure 7.8 describes average annual conditions. Superimposed on the changes of Figure 7.7 will be the variability of climate, in particular the likely increase in the incidence and intensity of climate extremes (***Houghton, 2009***).

The boxes in **Figure 3.10** illustrate some particular impacts of expected changes. Eight of the changes of particular concern are the following:

(1) Mentioned earlier in the chapter was that as the rate of warming increases, up to one-half of the mass of mountain glaciers and small ice caps outside the polar region may melt away over the next hundred years. In fact if current warming rates are maintained it is projected that Himalayan glaciers could decay by 80% of their area by the 2030s. Snow melt is an important source of run-off and watersheds will be severely affected by glacier and snow cover decline. As temperatures rise, winter run-off will initially increase while spring high water, summer and autumn flows will be reduced. **(2)** Many semi-arid areas (e.g. Mediterranean basin, western USA, and southern Africa) will suffer serious decreases in water resources due to climate change. These problems will be particularly acute in semi-arid or arid low-income countries, where precipitation and stream flow are concentrated over a few months and where the variability of precipitation is likely to increase as climate changes.

(3) Due to increases in population in addition to climate change, the number of people living in severely stressed river basins is projected to increase from about 1.5 billion in 1995 to 3 to 5 billion in 2050 for the SRES B2 scenario. **(4)** The more intense hydrological cycle associated with global warming will lead to increased frequency and intensity of both floods and droughts. Floods and droughts affect more people across the globe than all other natural disasters and their impact has been increasingly severe in recent decades. Increases by 2050 in many parts of the world in the frequency and severity of both floods and droughts of about a factor of 5 that were mentioned in Chapter 6 will have very large implications for water availability and management.

(5) Groundwater recharge will decrease considerably in some already water stressed regions where vulnerability may be exacerbated by increase in population and water demand. **(6)** Sea level rise together with greater use of groundwater will extend areas of salination of groundwater and estuaries, resulting in a decrease in fresh water availability for humans and ecosystems in coastal areas. **(7)** Higher water temperatures, increased precipitation intensity and longer periods of low flows exacerbate many forms of water pollution, with impacts on ecosystems, human health and water system reliability and operating costs. **(8)** A further reason, not unconnected with global warming, for the vulnerability of water supplies is the link between rainfall and changes in land use. Extensive deforestation can lead to large changes in rainfall. A similar tendency to reduced rainfall can be expected if there is a reduction in vegetation over large areas of semi-arid regions. Such changes can have a devastating and widespread effect and assist in the process of desertification. This is a potential threat to the drylands covering about one-quarter of the land area of the world (***Houghton, 2009***).

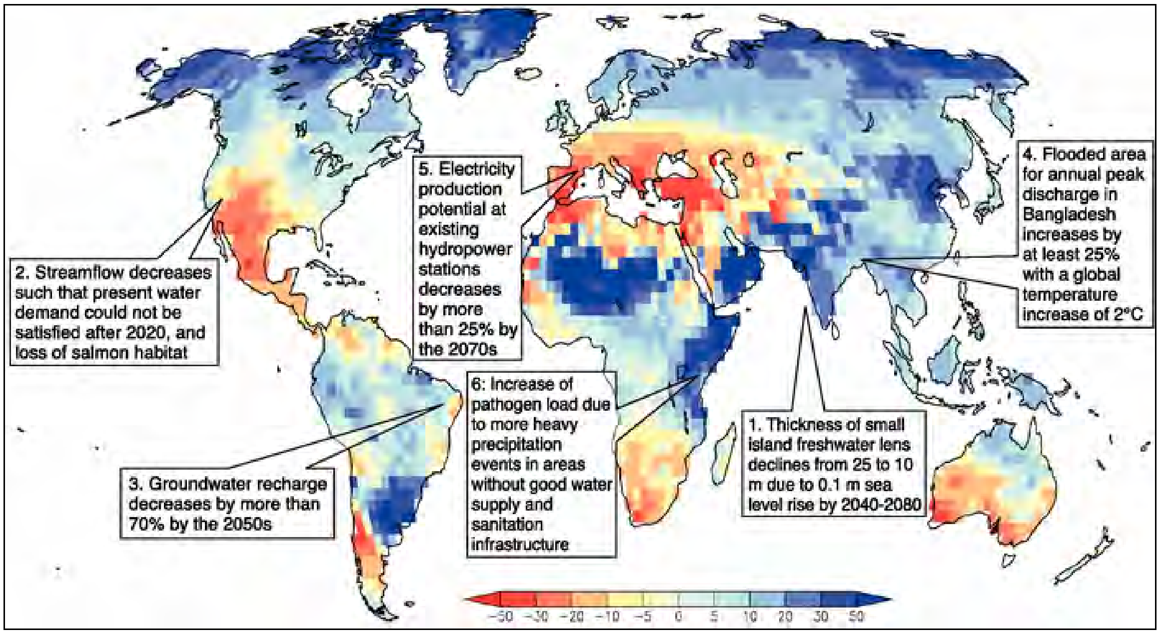


Figure 3.10: Illustrative map of future climate change impacts on fresh water which are a threat to the sustainable development of the affected regions. The background map is of the ensemble mean change in annual run-off in per cent between (1981–2000) and (2081– 2100) for the SRES A1B emissions scenario (http://www.ipcc.ch/publications_and_data/ar4/wg2/en/figure-3-8.html/ 10.1.12)

3.3 *Air pollution in a changing world*

3.3.1 *Introduction*

The principal basic principle of global warming can be understood by considering the radiation energy from the Sun that warms the Earth's surface and the thermal radiation from the Earth and the atmosphere that is radiated out to space. On average these two radiation streams must balance. If the balance is disturbed (for instance by an increase in atmospheric carbon dioxide) it can be restored by an increase in the Earth's surface temperature. But the question now is: how the Earth keeps warm? And to explain the processes that warm the Earth and its atmosphere, **Houghton (2009)** in the 4th Edition of his book "*Global Warming: the complete briefing*" stated that, if we will begin with a very simplified Earth. Suppose we could, all of a sudden, remove from the atmosphere all the clouds, the water vapour, the carbon dioxide and all the other minor gases and the dust, leaving an atmosphere of nitrogen and oxygen only. Everything else remains the same. What, under these conditions, would happen to the atmospheric temperature? The calculation is an easy one, involving a relatively simple radiation balance. Radiant energy from the Sun falls on a surface of one square metre in area outside the atmosphere and directly facing the Sun at a rate of about 1370 watts – about the power radiated by a reasonably sized domestic electric fire. However, few parts of the Earth's surface face the Sun directly and in any case for half the time they are pointing away from the Sun at night, so that the average energy falling on one square metre of a level surface outside the atmosphere is only one-quarter of this 1 or about 342 watts. As this radiation passes through the atmosphere a small amount, about 6%, is scattered back to space by atmospheric molecules. About 10% on average is reflected back to space from the land and ocean surface. The remaining 84%, or about 288 watts per square metre on average, remains actually to heat the surface – the power used by three good-sized incandescent electric light bulbs .

To balance this incoming energy, the Earth itself must radiate on average the same amount of energy back to space in the form of thermal radiation. All objects emit this kind of radiation; if they are hot enough we can see the radiation they emit. The Sun at a temperature of about 6000 °C looks white; an electric fire at 800 °C looks red. Cooler objects emit radiation that cannot be seen by our eyes and which lies at wavelengths beyond the red end of the spectrum – infrared radiation (sometimes called long wave radiation to distinguish it from the shortwave radiation from the Sun). On a clear, starry winter's night we are very aware of the cooling effect of this kind of radiation being emitted by the Earth's surface into space – it often leads to the formation of frost. The amount of thermal radiation emitted by the Earth's surface depends on its temperature – the warmer it is, the more radiation is emitted. The amount of radiation also depends on how absorbing the surface is; the greater the absorption, the more the radiation. Most of the surfaces on the Earth, including ice and snow, would appear 'black' if we could see them at infrared wave lengths; that mean that they absorb nearly all the thermal radiation which falls on them instead of reflecting it. It can be calculated 2 that the 288 W m^{-2} of incoming solar radiation received by the Earth's surface can be balanced by thermal radiation emitted by the surface at a temperature of –6 °C. 3 This is over 20 °C colder than is actually the case. In fact, an average of temperatures measured near the surface all over the Earth – over the oceans as well as the land– averaging, too, over the whole year, comes to about 15 °C. Some factor not yet taken into account is needed to explain this difference (***Houghton, 2009***).

3.3.2 *Effect of Climate Change on Air Quality*

Gas-phase chemical mechanisms are vital components of prognostic air quality models. The mechanisms are incorporated into modules that are used to calculate the chemical sources and sinks of O_3 and the precursors of particulates.

Fifty years ago essential atmospheric chemical processes, such as the importance of the hydroxyl radical, were unknown and crude air quality models incorporated only a few parameterized reactions obtained by fitting observations. Over the years, chemical mechanisms for air quality modeling improved and became more detailed as more experimental data and more powerful computers became available. However it will not be possible to incorporate a detailed treatment of the chemistry for all known chemical constituents because there are thousands of organic compounds emitted into the atmosphere. Some simplified method of treating atmospheric organic chemistry is required to make air quality modeling computationally possible. The majority of the significant differences between air quality mechanisms are due to the differing methods of treating this organic chemistry. The gas-phase chemistry of the polluted atmosphere determines the effect of emissions on the production of ozone (O_3), particulate matter, acids and other air pollutants. The chemical mechanism is developed from laboratory and field measurement data and consists of chemical species, reactions, rate constants and photochemical data (used to calculate photolysis frequencies). NO_x, organic compounds and sulfur compounds are the key chemical compounds treated by air quality chemical mechanisms for modeling the polluted troposphere. The mechanism is translated into differential equations. The differential equations are coded into computer models that include numerical solvers that are used to simulate the chemical fate of air pollutants. Therefore, mechanism developers must consider both chemistry and the limitations of computational resources (***Stockwell et al. 2012***).

It could be noticed that, the gas-phase production of air pollutants is initiated by photolysis and involves a complicated series of free radical reactions. During the nighttime the reaction of O_3 with alkenes and NO_2 also leads to the production of free radicals. There are a very high number of chemical compounds emitted into the atmosphere. Tens of thousands of compounds react through millions of reactions. In comparison a relatively small number of reactions have been studied with their rate constants known (for room temperature) much better than their product yields. The knowledge base is very incomplete relative to the complex nature of atmospheric chemistry. There are severe computational limitations on the size of a chemical mechanism that can be used for air quality modeling. Air quality models with high spatial resolution have tens of thousands of grid boxes and therefore each prognostic chemical species included in the model adds tens of thousands of differential equations to solve and much additional memory storage. The chemical mechanism used in a meteorological air quality model must be very simple in contrast to real atmospheric chemistry. There are several chemical mechanisms that have been developed for air quality modeling. More data from the laboratory, environmental reaction chamber and field are required to improve atmospheric chemical mechanisms. It is very possible that there are major surprises to be discovered especially in the chemistry of HO_x and other processes that control O_3 and particle formation (***Chen et al. 2010***).

Air quality is strongly dependent on weather and is therefore sensitive to climate change. Recent studies have provided estimates of this climate effect through correlations of air quality with meteorological variables, perturbation analyses in chemical transport models (CTMs), and CTM simulations driven by general circulation model (GCM) simulations of 21st-century climate change. Air pollution results from the combination of high emissions and unfavorable weather. Air quality managers seek to protect public health through emission controls. The resulting improvements in air quality may be modulated by changes in weather statistics, i.e., changes in climate. As we enter an era of rapid climate change, the implications for air quality need to be better understood, both for the purpose of air quality management and as one of the societal consequences of climate change (***Jacob and Winner, 2009***).

Emissions of CO_2, methane, nitrous oxide and of reactive gases such as sulphur dioxide, nitrogen oxides, carbon monoxide and hydrocarbons, which lead to the formation of secondary pollutants including aerosol particles and tropospheric ozone, have increased substantially in response to human activities. As a result, biogeochemical cycles have been perturbed significantly. Nonlinear interactions between the climate and biogeochemical systems could amplify (positive feedbacks) or attenuate (negative feedbacks) the disturbances produced by human activities. Observed increases in atmospheric methane concentration, compared with pre-industrial estimates, are directly linked to human activity, including agriculture, energy production, waste management and biomass burning. Constraints from methyl chloroform observations show that there have been no significant trends in hydroxyl radical (OH) concentrations, and hence in methane removal rates, over the past few decades. The recent slowdown in the growth rate of atmospheric methane since about 1993 is thus *likely* due to the atmosphere approaching equilibrium during a period of near-constant total emissions (***Denman et al. 2007***).

However, future methane emissions from wetlands are *likely* to increase in a warmer and wetter climate, and to decrease in a warmer and drier climate. No long-term trends in the tropospheric concentration of OH are expected over the next few decades due to offsetting effects from changes in nitric oxides (NO_x), carbon monoxide, organic emissions and climate change. Interannual variability of OH may continue to affect the variability of methane. New model estimates of the global tropospheric ozone budget indicate that input of ozone from the stratosphere (approximately 500 Tg yr^{-1}) is smaller than estimated in the TAR (770 Tg yr^{-1}), while the photochemical production and destruction rates (approximately 5,000 and 4,500 Tg yr^{-1}, respectively) are higher than estimated in the TAR (3,400 and 3,500 Tg yr^{-1}). This implies greater sensitivity of ozone to changes in tropospheric chemistry and emissions. Observed increases in NO_x and nitric oxide emissions, compared with pre-industrial estimates, are *very likely* directly linked to 'acceleration' of the nitrogen cycle driven by human activity, including increased fertilizer use, intensification of agriculture and fossil fuel combustion (***Denman et al. 2007***).

Future climate change may cause either an increase or a decrease in background tropospheric ozone, due to the competing effects of higher water vapour and higher stratospheric input; increases in regional ozone pollution are expected due to higher temperatures and weaker circulation. Future climate change may cause significant air quality degradation by changing the dispersion rate of pollutants, the chemical environment for ozone and aerosol generation and the strength of emissions from the biosphere, fires and dust. The sign and magnitude of these effects are highly uncertain and will vary regionally. The future evolution of stratospheric ozone, and therefore its recovery following its destruction by industrially manufactured halocarbons, will be influenced by stratospheric cooling and changes in the atmospheric circulation resulting from enhanced CO_2 concentrations. With a possible exception in the polar lower stratosphere where colder temperatures favor ozone destruction by chlorine activated on polar stratospheric cloud particles, the expected cooling of the stratosphere should reduce ozone depletion and therefore enhance the ozone column amounts (***Denman et al. 2007***).

The two air pollutants of most concern for public health are surface ozone and particulate matter. Ozone is produced in the troposphere by photochemical oxidation of CO, methane, and non-methane volatile organic compounds (NMVOCs) by the hydroxyl radical (OH) in the presence of reactive nitrogen oxides ($NO_x \equiv NO + NO_2$). NMVOCs, CO, and NO_x have large combustion sources. Vegetation is a large NMVOC source. Methane has a number of biogenic and anthropogenic sources. OH originates mainly from atmospheric oxidation of water vapor and cycles in the atmosphere with other hydrogen oxide (HO_x) radicals. Ozone pollution is in general mostly a summer problem because of the photochemical nature of the source. Ozone production is usually limited by the supply of HO_x and NO_x, but can also be NMVOC-limited under highly polluted conditions and outside the summer season. The principal global sink for Tropospheric ozone is photolysis in the presence of water vapor. Uptake by vegetation (dry deposition) is also an important sink in the continental boundary layer (< 2 km).Wet deposition is negligible as ozone and its major precursors have low solubility in water. The atmospheric lifetime of ozone ranges from a few days in the boundary layer to weeks in the free troposphere. Ozone and its anthropogenic precursors ventilated from the source continents and transported on hemispheric scales in the free troposphere add a significant background to surface ozone which is of increasing concern for meeting air quality standards (**Table 3.11**; ***UNECE, 2007***).

Changes in climate affect air quality by perturbing ventilation rates (wind speed, mixing depth, convection, and frontal passages), precipitation scavenging, dry deposition, chemical production and loss rates, natural emissions, and background concentrations. The potential importance of this effect can be appreciated by considering the observed interannual variability in air quality. Fig.1 shows a 1980–2006 record of the number of exceedances of the U.S. air quality standard for ozone (80 ppb, 8-h average) in the Northeast. There is a long-term decrease attributable to reductions in anthropogenic emissions (NO_x, NMVOCs), but also a large year-to year variability due to weather. Ozone is strongly correlated with temperature. The summer of 1988 was the hottest on record in the Northeast and experienced a record high number of exceedances. The summer of 1992 was the coolest in the 1980–2006 record due to the eruption of Mt. Pinatubo and it had a low number of exceedances. If conditions like 1988 become more frequent as a result of global warming, the implications for air quality could be severe. Similar inferences can be made for Europe, where the summer 2003 heat wave was associated with exceptionally high ozone (***Solberg et al. 2008***).

Ozone and PM interact with solar and terrestrial radiation and as such are recognized as important climate forcing agents (***Forster et al. 2007***). Because of this dual role, the effect of climate change on surface air quality is often framed in the broader context of chemistry-climate interactions, as shown diagrammatically in **Figure 3.11** In this diagram, an external forcing from change in anthropogenic emissions triggers interactive changes within the chemistry climate- emissions system, and the perturbation to surface air quality is a consequence of these interactive changes. Examples of forcings include anthropogenic emissions of CO_2 (driving change in climate), NO_x (driving atmospheric chemistry), or elemental carbon (driving change in climate as well as direct change in air quality). Change in atmospheric chemistry affects air quality (ozone and PM) and climate (ozone, PM, methane). Change in climate affects natural emissions (biosphere, dust, fires, lightning) with implications for air quality. Chemistry-climate interactions involve a number of possible feedbacks, as illustrated in **Figure 3.12**, and these are in general poorly understood (***Denman et al. 2007***).

An important issue is whether climate change could affect the dependence of ozone on NO_x and NMVOC emissions in a way that would compromise the effectiveness of current emission control strategies. **Liao et al. (2007)** examined this issue for the U.S. with the model of **Tagaris et al. (2007)** and found no significant effect, implying that emission control strategies designed for the present climate should still be successful in the future climate. Model simulations by **Baertsch-Ritter et al. (2004)** for the Milan urban plume show increased ozone sensitivity to NMVOCs as temperature increases, due to the reduced thermal stability of PAN and hence higher concentrations of NO_x. By contrast, model simulations by **Cardelino and Chameides (1990)** for the Atlanta urban plume show increased ozone sensitivity to NOx as temperature increases, due to increasing isoprene emission and supply of HO_x radicals. The opposite responses of the Milan and Atlanta plumes likely reflect regional differences in biogenic NMVOC emissions, but the point from both studies is that sensitivities of ozone to NO_x and NMVOC emissions could be affected by climate change. Pollutant emissions are also expected to respond to climate change. Higher temperatures increase the demand for air conditioning in summer when ozone and PM concentrations are highest. Evaporative emissions of anthropogenic NMVOCs also increase, although the effect determined for mobile sources is relatively weak, in the range 1.3–5% K^{-1} (***Rubin et al. 2006***).

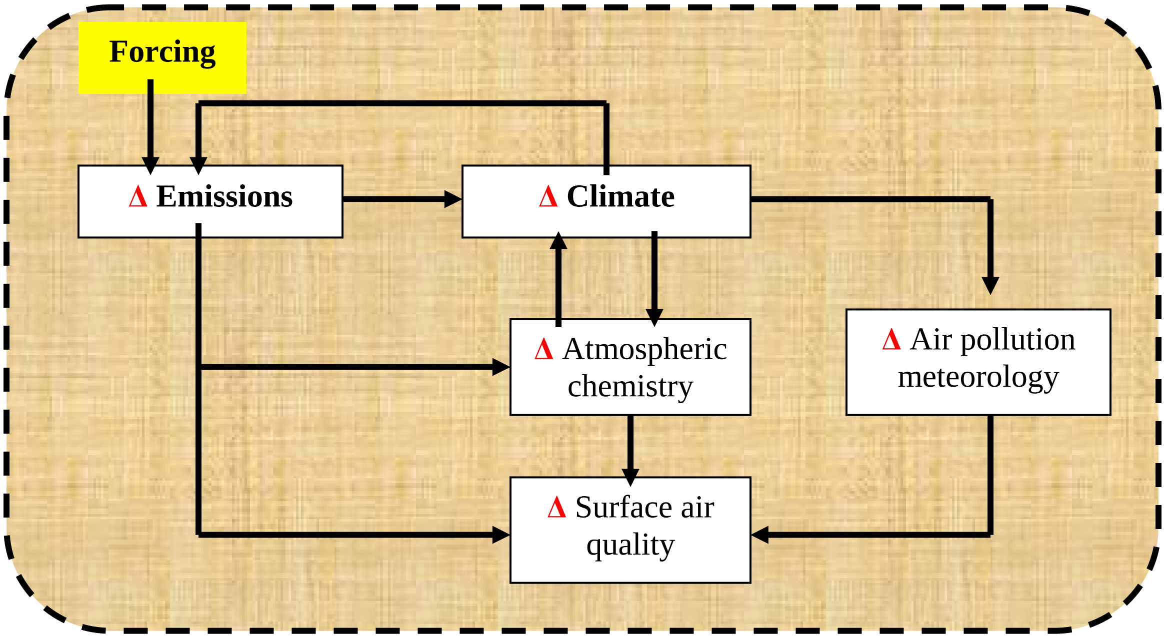


Figure 3.11: Effect of climate change on surface air quality placed in the broader context of chemistry-climate interactions. Change is forced by a perturbation to anthropogenic emissions resulting from socio-economic factors external to the chemistry-climate system. This forcing triggers interactive change (Δ) within the chemistry-climate system resulting in perturbation to surface air quality (adapted from ***Jacob and Winner, 2009***)

Table 3.11: The composition of the atmosphere, the main constituents (nitrogen and oxygen) and the greenhouse gases as in 2007 (adapted from ***Houghton, 2009***)

Gas	Mixing ratio or mole fraction expressed as fraction* or parts per million (ppm)
Nitrogen (N_2)	0.78*
Oxygen (O_2)	0.21*
Water vapour (H_2O)	Variable (0–0.02*)
Carbon dioxide (CO_2)	380
Methane (CH_4)	1.8
Nitrous oxide (N_2O)	0.3
Chlorofluorocarbons	0.001
Ozone (O_3)	Variable (0–1000)

[a] For definition see Glossary.

Finally, as the world moves forward to develop energy and transportation policies directed at mitigating climate change, it will be important to factor into these policies the co- or dis-benefits for regional air pollution. Energy policy offers an opportunity to dramatically improve air quality through transition to nonpolluting energy sources. By contrast, a switch to biofuels would not necessarily benefit air quality and could possibly be detrimental (***Jacobson, 2007***).

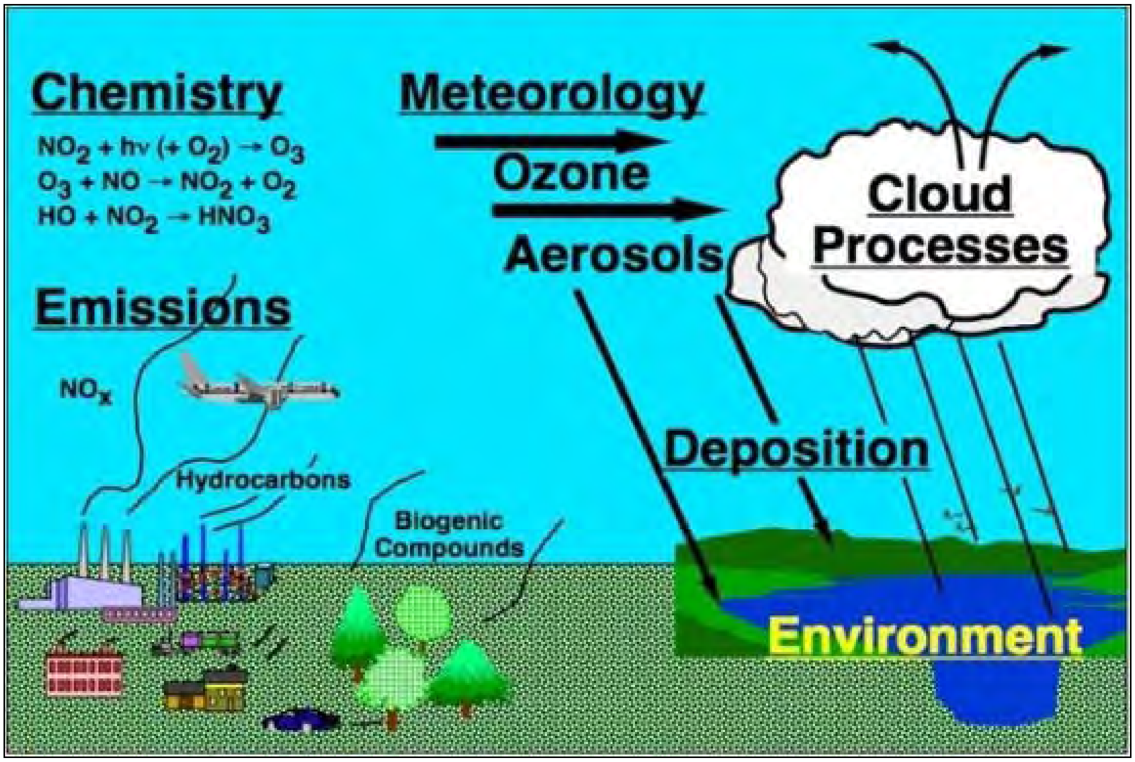


Figure 3.12: Chemistry-climate interactions involve a number of possible feedbacks (http://www.mdpi.com/2073-4433/3/1/1/ 13.1.2012)

3.3.3 *The Greenhouse Gases and its Effects*

It could be defined the greenhouse effects as the cause of *global warming*. Incoming *solar radiation* is transmitted by the *atmosphere* to the Earth's surface, which it warms. The energy is retransmitted as *thermal radiation*, but some of it is absorbed by *molecules* of *greenhouse gases* instead of being retransmitted out to space, thus warming the atmosphere. The name comes from the ability of greenhouse glass to transmit incoming solar radiation but retain some of the outgoing thermal radiation to warm the interior of the greenhouse. The 'natural' greenhouse effect is due to the greenhouse gases present for natural reasons, and is also observed for the neighboring planets in the solar system. The 'enhanced' greenhouse effect is the added effect caused by the greenhouse gases present in the atmosphere due to human activities, such as the burning of *fossil fuels* and *deforestation* (***Houghton, 2009***).

The 'greenhouse effect' is one of many physical, chemical and biological natural processes that shape Earth's climate. The greenhouse effect plays a major part in creating our warm environment around the Earth's surface. The atmosphere, consisting primarily of nitrogen (78%) and oxygen (21%), is essentially transparent to incoming (shortwave) solar radiation and to the long wave radiation emitted from the Earth's surface. Around 30% of the incoming solar radiation is reflected back to space by clouds, aerosols (small particles in the atmosphere) and light colored regions of the Earth (e.g., covered by snow, ice or desert) and the rest is absorbed by the Earth's surface and, to a lesser extent, the atmosphere and re-emitted as long wave radiation. Other constituents of the atmosphere, such as water vapour, carbon dioxide (CO_2) and trace gases like methane and nitrous oxide, are largely transparent to the incoming solar radiation but absorb and re-emit long wave radiation. Some of the long wave radiation is emitted back to space but some is trapped by the blanket of greenhouse gases in the atmosphere resulting in a warming of the Earth's surface. Water vapour and CO_2 are the most important and abundant of the greenhouse gases. Water vapour is not well mixed in the atmosphere so its effects can vary regionally (***Poloczanska and Richardson, 2009***).

Discovery of the Greenhouse Effect

Without the natural *greenhouse effect* on Earth, life as it exists today would not be possible. In order to understand the cause and effects of *global warming*, it is first necessary to understand the Earth's natural greenhouse effect and the roles of the various *greenhouse gases*, such as *carbon dioxide* (CO_2). It was during the 19^{th} century that scientists realized that gases—such as CO_2—found within the *atmosphere* cause a "greenhouse effect" that regulates the atmosphere's temperature. Ironically, the discovery of the greenhouse effect did not happen because scientists were trying to understand global warming; it happened because they were searching for the mechanism that triggered ice ages. In an effort to understand the connection between CO_2 and glacial periods, their interest was in studying the time intervals when concentrations of CO_2 were at their lowest, which correlated with the glacial periods in the Earth's past climate (***Casper, 2010***).

The beginning of the discovery process began with ***Joseph Fourier*** in the 1820s. During this time period, scientists were beginning to understand that the gases that composed the atmosphere may trap the heat received in the atmosphere from the Sun. Also at this time, ***John Tyndall***, a natural philosopher, was interested in finding out whether any gases in the atmosphere could actually trap heat rays. In 1859, through a series of lab analyses, he was able to identify several gases that were able to trap and hold heat. The most important of these gases were water vapor (H_2O) and CO_2. Later, in 1896, ***Svante Arrhenius***, a Swedish chemist/physicist, who was working with data on the prehistoric ice ages, was able to determine in his laboratory that by cutting the amount of CO_2 in the atmosphere by half, it could lower the temperature over Europe about 7–9°F (4–5°C) — roughly the equivalent of what would trigger another ice age. In order for this to happen, however, the effect would have to be global. From this point, Arrhenius turned to ***Arvid Högbom***, who added a modern twist to the analysis. He discovered that various human activities were adding CO_2 to the atmosphere at a rapid rate. At that time, he thought that the addition was not serious enough for alarm—it was not much different from other natural processes like erupting volcanoes. What he was concerned about, however, was that if the volumes continued being released into the atmosphere, it would not be long before they did start to negatively affect its quality. Arrhenius suggested that at the current rate of coal burning, the atmosphere could begin to start warming in a few centuries. About that time, Thomas C. Chamberlin, an American geologist, became interested in atmospheric CO_2 levels, and the Swedish scientist ***Knut Ångström*** discovered that greenhouse gases do cause temperature to rise by retaining the heat instead of letting it escape to space. This added additional enlightenment to the beginning of the global warming theory (***Casper, 2010***).

The Greenhouse Effect

The Earth needs the natural greenhouse effect. It is the process in which the *emission* of infrared radiation by the atmosphere warms the planet's surface. The atmosphere naturally acts as an insulating blanket, which is able to trap enough solar energy to keep the global average temperature in a comfortable range in which to support life. This insulating blanket is actually a collection of several atmospheric gases, some of them in such small amounts that they are referred to as trace gases. The framework in which this system works is often referred to as the greenhouse effect because this global system of insulation is similar to that which occurs in a greenhouse nursery for plants. The gases are relatively transparent to incoming visible light from the Sun, yet opaque to the energy radiated from the Earth. These gases are the reason why the Earth's atmosphere does not scorch during the day and freeze at night. Instead, the atmosphere contains molecules that absorb and reradiate the heat in all directions, which reduces the heat lost back to space. It is the greenhouse gas molecules that keep the Earth's temperature ranges within comfortable limits. Without the natural greenhouse effect, life would not be possible on Earth. In fact, without the greenhouse effect to regulate the atmospheric temperature, the Sun's heat would escape and the average temperature would drop from 57°F to –2.2°F (14°C to –18°C); a temperature much too cold to support the diversity of life that exists today on the planet (***Casper, 2010***).

The gases nitrogen and oxygen that make up the bulk of the atmosphere (**Table 3.12** gives details of the atmosphere's composition) neither absorb nor emit thermal radiation. It is the water vapour, carbon dioxide and some other minor gases present in the atmosphere in much smaller quantities that absorb some of the thermal radiation leaving the surface, acting as a partial blanket for this radiation and causing the difference of 20 to 30 °C between the actual average surface temperature on the Earth of about 15 °C and the temperature that would apply if greenhouse gases were absent. This blanketing is known as the *natural greenhouse effect* and the gases are known as greenhouse gases (**Figure 3.13**). It is called 'natural' because all the atmospheric gases (apart from the chlorofluorocarbons – CFCs) were there long before human beings came on the scene. Later on I will mention the *enhanced greenhouse effect*: the added effect caused by the gases present in the atmosphere due to human activities such as deforestation and the burning of fossil fuels (***Houghton, 2009***).

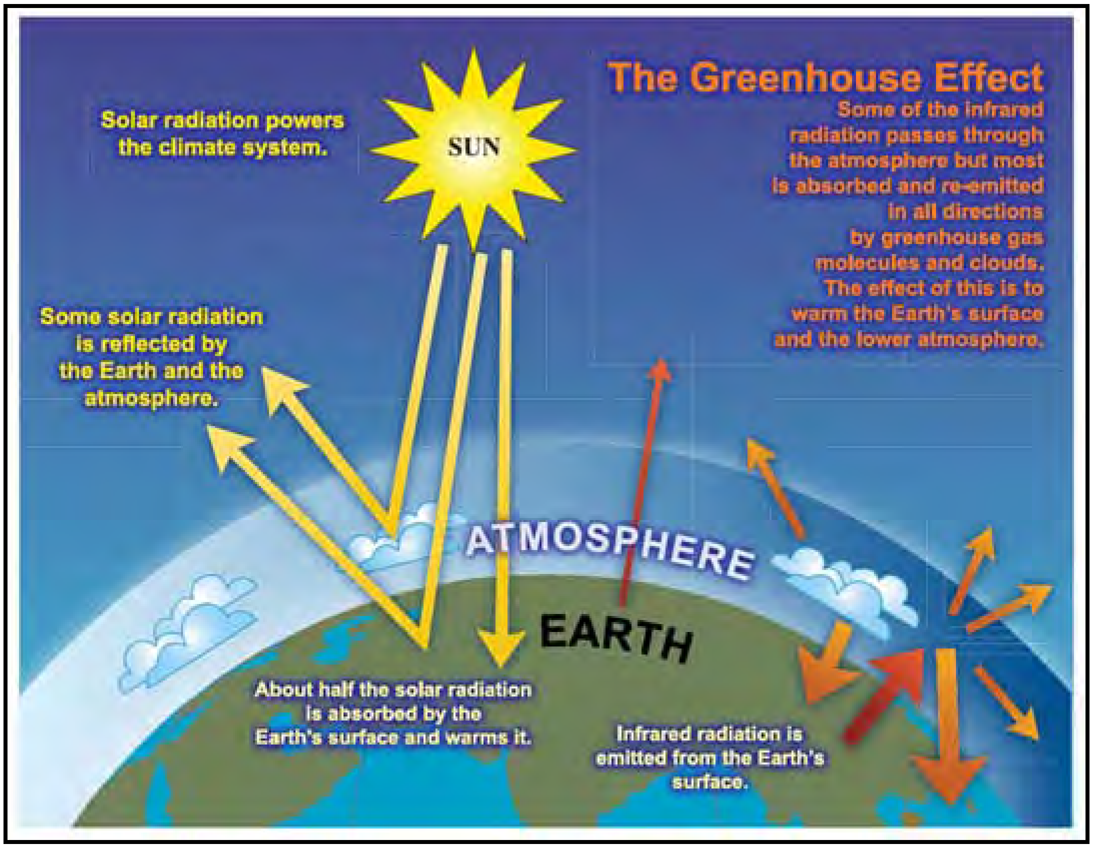


Figure 3.13: Schematic of the natural greenhouse effect (from ***Le Treut et al. 2007***) (http://www.global-greenhouse-warming.com/graphs-diagrams-of-global-warming-and-climate.html/ 25.12.2011)

The basic science of the greenhouse effect has been known since early in the nineteenth century when the similarity between the radiative properties of the

Earth's atmosphere and of the glass in a greenhouse was first pointed out – hence the name 'greenhouse effect'. In a greenhouse, visible radiation from the Sun passes almost unimpeded through the glass and is absorbed by the plants and the soil inside. The thermal radiation that is emitted by the plants and soil is, however, absorbed by the glass that re-emits some of it back into the greenhouse. The glass thus acts as a 'radiation blanket' helping to keep the greenhouse warm. However, the transfer of radiation is only one of the ways heat is moved around in a greenhouse. A more important means of heat transfer is convection, in which less dense warm air moves upwards and more dense cold air moves downwards. A familiar example of this process is the use of convective electric heaters in the home, which heat a room by stimulating convection in it. The situation in the greenhouse is therefore more complicated than would be the case if radiation were the only process of heat transfer (***Houghton, 2009***).

Mixing and convection are also present in the atmosphere, although on a much larger scale, and in order to achieve a proper understanding of the greenhouse effect, convective heat transfer processes in the atmosphere must be taken into account as well as radiative ones. Within the atmosphere itself (at least in the lowest three-quarters or so of the atmosphere up to a height of about 10 km which is called the troposphere) convection is, in fact, the dominant process for transferring heat. It acts as follows. The surface of the Earth is warmed by the sunlight it absorbs. Air close to the surface is heated and rises because of its lower density. As the air rises it expands and cools – just as the air cools as it comes out of the valve of a tyre. As some air masses rise, other air masses descend, so the air is continually turning over as different movements balance each other out – a situation of convective equilibrium. Temperature in the troposphere falls with height at a rate determined by these convective processes; the fall with height (called the lapse rate) turns out on average to be about 6 °C per kilometer of height (***Houghton, 2009***).

The numbers in **Figure 3.14** demonstrate the required balance: 235 watts per square metre on average coming in and 235 watts per square metre on average going out. The temperature of the surface and hence of the atmosphere above adjusts itself to ensure that this balance is maintained. It is interesting to note that the greenhouse effect can only operate if there are colder temperatures in the higher atmosphere. Without the structure of decreasing temperature with height, therefore, there would be no greenhouse effect on the Earth. No one doubts the reality of the natural greenhouse effect, which keeps us over 20 °C warmer than we would otherwise be. The science of it is well understood; it is similar science that applies to the enhanced greenhouse effect. Study of climates of the past gives some clues about the greenhouse effect. First, however, the greenhouse gases themselves must be considered. How does carbon dioxide get into the atmosphere, and what other gases affect global warming?

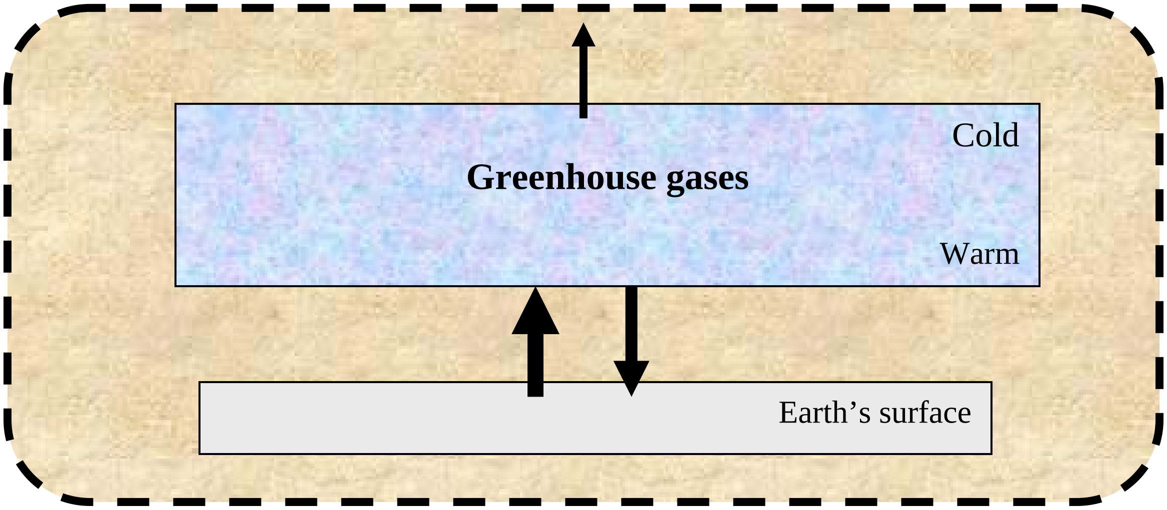


Figure 3.14: The blanketing effect of greenhouse gases (adapted from ***Houghton, 2009***)

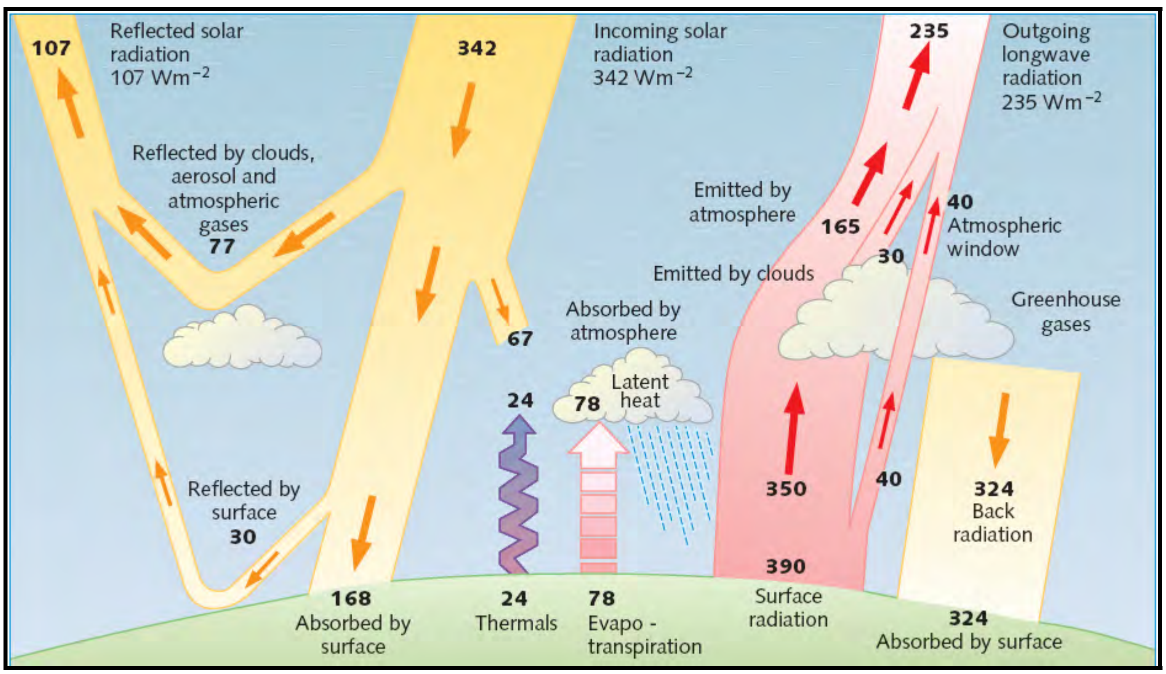


Figure 3.15: Components of the radiation (in watts per square metre) which on average enter and leave the Earth's atmosphere and make up the radiation budget for the atmosphere. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by long wave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates long wave energy back to Earth as well as out to space (http://sxxz.blogspot.com/2010_09_01_archive.html/ 25.12.2011)

Radiation is emitted out to space by these gases from levels somewhere near the top of the atmosphere – typically from between 5 and 10 km high. Here, because of the convection processes mentioned earlier, the temperature is much colder – 30 to 50 °C or so colder – than at the surface. Because the gases are cold, they emit correspondingly less radiation. What these gases have to do, therefore, is absorb some of the radiation emitted by the Earth's surface but then to emit much less radiation out to space. They, therefore, act as a radiation blanket over the surface (note that the outer surface of a blanket is colder than inside the blanket) and help to keep it warmer than it would otherwise be (**Figure 3.15**; ***Houghton, 2009***).

The Natural and Enhanced Greenhouse Effect

In this "greenhouse environment," it is the combination of water vapor and trace gases that are responsible for trapping the heat radiated from the Sun. The natural amount keeps the Earth habitable. Without this trapped warmth, the Earth would have an average temperature of –0.4°F (–18°C). If this were the case, the Earth would look much different—there would most likely be very little, if any, liquid water available. The entire Earth would have an *ecosystem* similar to that of the harshest areas in Antarctica. The Earth's natural greenhouse effect is critical for the survival and diversity of life. Since the Industrial Revolution (over the past 250 years or so), the natural greenhouse effect has been augmented by human interference. CO_2, one of the atmosphere's principal greenhouse gases, has been altered to such an extent by human activity that the natural greenhouse effect is no longer in balance. The Earth's energy balance now must contend with what is referred to as the "enhanced greenhouse effect" or "anthropogenic greenhouse warming." CO_2 is being added in voluminous amounts as a result of human activity; *deforestation*; agricultural practices; the burning of fossil fuels for transportation; urban development; heating and cooling homes; and industrial processes. CO_2 in the atmosphere has increased 31 percent since 1895. Concentration of other greenhouse gases, such as *methane* and *nitrous oxides* (also related to human activity) have increased 151 percent and 17 percent, respectively. This enhanced greenhouse effect began in the age of the Industrial Revolution of the 1700s. At that time, CO_2 content in the atmosphere was 280 *parts per million (ppm)*. By 1958, it had increased to 315 ppm; by 2004, 378 ppm; by 2005, 379 ppm; and by 2007, 383 ppm. According to ***James E. Hansen***, a world-renowned expert on global warming and *climate* change in New York at NASA's Goddard Institute for Space Studies (GISS), "Climate is nearing dangerous tipping points. We have already gone too far. We must draw down atmospheric CO_2 to preserve the planet we know. A level of no more than 350 ppm is still feasible, with the help of reforestation and improved agricultural practices, but just barely—time is running out" (***Casper, 2010***).

Which are the most important greenhouse gases?

Greenhouse gases are *molecules* in the Earth's *atmosphere* such as *carbon dioxide* (CO_2), methane (CH_4) and CFCs which warm the atmosphere because they absorb some of the *thermal radiation* emitted from the Earth's surface. The greenhouse gases are those gases in the atmosphere which, by absorbing thermal radiation emitted by the Earth's surface, have a blanketing effect upon it. The most important of the greenhouse gases is water vapour, but its amount in the atmosphere is not changing directly because of human activities. The important greenhouse gases that are directly influenced by human activities are carbon dioxide, methane, nitrous oxide, the chlorofluorocarbons (CFCs) and ozone. Carbon dioxide is the most important of the greenhouse gases that are increasing in atmospheric concentration because of human activities. If, for the moment, we ignore the effects of the CFCs and of changes in ozone, which vary considerably over the globe and which are therefore more difficult to quantify, the increase in carbon dioxide (CO_2) has contributed about 72% of the enhanced greenhouse effect to date, methane (CH_4) about 21% and nitrous oxide (N_2O) about 7% (***Houghton, 2009***).

It is the existence of trace gases in the atmosphere that act like the glass in a greenhouse. The trace gases serve to trap the heat energy from the Sun close to Earth. Most greenhouse gases occur naturally. Greenhouse gases are cycled through the global biogeochemical system. It is the greenhouse gases added by human activity that are trapping too much heat today and causing the atmosphere to overheat. There are several different types of greenhouse gases, some existing in greater quantities than others. They include: (1) water vapor, (2) CO_2, (3) methane, (4) nitrous oxide, and (5) halocarbons. Greenhouse gases capture 70 to 85 percent of the energy in up going thermal radiation emitted from the Earth's surface (***Casper, 2010***).

(1) *Carbon dioxide* (CO_2):

CO_2 is emitted principally from the burning of fossil fuels, both in large combustion units such as those used for electric power generation and in smaller, distributed sources such as automobile engines and furnaces used in residential and commercial buildings. CO_2 emissions also result from some industrial and resource extraction processes, as well as from the burning of forests during land clearance. Carbon dioxide capture and storage (CCS) would most likely be applied to large point sources of CO_2, such as power plants or large industrial processes. Some of these sources could supply decarbonized fuel such as hydrogen to the transportation, industrial and building sectors, and thus reduce emissions from those distributed sources (***IPCC, 2005***).

In 1992, international concern about climate change led to the United Nations Framework Convention on Climate Change (UNFCCC). The ultimate objective of that Convention is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system". From this perspective, the context for considering CCS (and other mitigation options) is that of a world constrained in CO_2 emissions, consistent with the international goal of stabilizing atmospheric greenhouse gas concentrations. Most scenarios for global energy use project a substantial increase of CO_2 emissions throughout this century in the absence of specific actions to mitigate climate change. They also suggest that the supply of primary energy will continue to be dominated by fossil fuels until at least the middle of the century. The magnitude of the emissions reduction needed to stabilize the atmospheric concentration of CO_2 will depend on both the level of future emissions (the baseline) and the desired target for long-term CO_2 concentration: the lower the stabilization target and the higher the baseline emissions, the larger the required reduction in CO_2 emissions (***IPCC, 2005***).

IPCC's Third Assessment Report (TAR) states that, depending on the scenario considered, cumulative emissions of hundreds or even thousands of gigatonnes (Gt) of CO_2 would need to be prevented during this century to stabilize the CO_2 concentration at 450 to 750 ppm (by volume). The TAR also finds that, "most model results indicate that known technological options could achieve a broad range of atmospheric CO_2 stabilization levels", but that "no single technology option will provide all of the emissions reductions needed". Rather, a combination of mitigation measures will be needed to achieve stabilization. These known technological options are available for stabilization, although the TAR cautions that, "implementation would require associated socio-economic and institutional changes" (***IPCC, 2005***).

As noted earlier, CO_2 emissions from human activity arise from a number of different sources, mainly from the combustion of fossil fuels used in power generation, transportation, industrial processes, and residential and commercial buildings. CO_2 is also emitted during certain industrial processes like cement manufacture or hydrogen production and during the combustion of biomass. Globally, emissions of CO_2 from fossil-fuel use in the year 2000 totalled about 23.5 Gt CO_2 yr^{-1} (6 Gt C yr^{-1}). Of this, close to 60% was attributed to large (> 0.1 Mt CO_2 yr^{-1}) stationary emission sources. However, not all of these sources are amenable to CO_2 capture. Although the sources evaluated are distributed throughout the world, the database reveals four particular clusters of emissions: North America (Midwest and eastern USA), Europe (northwest region), East Asia (eastern coast of China) and South Asia (Indian subcontinent). By contrast, large-scale biomass sources are much smaller in number and less globally distributed. Currently, the vast majority of large emission sources have CO_2 concentrations of less than 15% (in some cases, substantially less). However, small portions (less than 2%) of the fossil fuel-based industrial sources have CO_2 concentrations in excess of 95%. The high-concentration sources are potential candidates for the early implementation (***IPCC, 2005***).

Carbon dioxide provides the dominant means through which carbon is transferred in nature between a number of natural carbon reservoirs – a process known as the carbon cycle. We contribute to this cycle every time we breathe. Using the oxygen we take in from the atmosphere, carbon from our food is burnt and turned into carbon dioxide that we then exhale; in this way we are provided with the energy we need to maintain our life. Animals contribute to atmospheric carbon dioxide in the same way; so do fires, rotting wood and decomposition of organic material in the soil and elsewhere. To offset these processes of respiration whereby carbon is turned into carbon dioxide, there are processes involving photosynthesis in plants and trees which work the opposite way; in the presence of light, they take in carbon dioxide, use the carbon for growth and return the oxygen back to the atmosphere. Both respiration and photosynthesis also occur in the ocean (**Table 3.12**; ***Houghton, 2009***).

Table 3.12: Components of annual average global carbon budget for 1980s and 1990s in gigatonnes (Gt) of carbon per year (adapted from ***Houghton, 2009***)

	1980s	1990s	2000–2005
Emissions (fossil fuel, cement)	5.4 ± 0.3	6.4 ± 0.4	7.2 ± 0.3
Atmospheric increase	3.3 ± 0.1	3.2 ± 0.1	4.1 ± 0.1
Ocean–atmosphere flux	–1.8 ± 0.8	–2.2 ± 0.4	–2.2 ± 0.5
Land–atmosphere flux *	–0.3 ± 0.9	–1.0 ± 0.6	–0.9 ± 0.6
* *partitioned as follows*			
Land-use change	1.4 (0.6 to 2.3)	1.6 (0.5 to 2.7)	not available
Residual terrestrial sink	–1.7 (–3.4 to 0.2)	–2.6 (–4.3 to –0.9)	not available

Positive values are fluxes to the atmosphere
Negative values represent uptake from the atmosphere

Although not the only greenhouse gas, CO_2 does seem to be the one most focused on because it is one of the most important and prevalent. It makes up about 25 percent of the natural greenhouse effect. It is so prominent because there are several natural processes that put it in the atmosphere, such as the following:
Forest fires: When trees are burned, the CO_2 stored within them is released into the atmosphere.

- *Volcanic eruptions*: CO_2 is one of the gases released in abundance by volcanoes.
- *Oceans*: Oceans both absorb and release enormous amounts of CO_2. Historically, they have served as a major storage facility of CO_2 put into the atmosphere from human sources. Recently, however, scientists at NASA and NOAA have determined that the oceans have become nearly saturated and are approaching their limits as a carbon store.
- *Trees, plants, grasses, and other vegetation* serve as significant stores of *carbon.* When they die and decompose, half of their stored carbon is released into the atmosphere in the form of CO_2.

- *When vegetation dies*, the other half of their stored carbon is absorbed by the soil. Over time, some of this carbon is released into the atmosphere as CO_2.
- *Any life-form* that consumes plants that contain carbon also emit CO_2 into the atmosphere through breathing. This includes animals, insects, and even humans (***Casper, 2010***).

The main greenhouse gases

Greenhouse gases	Chemical formula	Pre-industrial concentration	Concentration in 1994	Atmospheric lifetime (years)***	Anthropogenic sources	Global warming potential (GWP)*
Carbon-dioxide	CO_2	278 000 ppbv	358 000 ppbv	Variable	Fossil fuel combustion Land use conversion Cement production	1
Methane	CH_4	700 ppbv	1721 ppbv	12,2 +/- 3	Fossil fuels Rice paddies Waste dumps Livestock	21 **
Nitrous oxide	N_2O	275 ppbv	311 ppbv	120	Fertilizer industrial processes combustion	310
CFC-12	CCl_2F_2	0	0,503 ppbv	102	Liquid coolants. Foams	6200-7100 ****
HCFC-22	$CHClF_2$	0	0,105 ppbv	12,1	Liquid coolants	1300-1400 ****
Perfluoromethane	CF_4	0	0,070 ppbv	50 000	Production of aluminium	6 500
Sulphur hexa-fluoride	SF_6	0	0,032 ppbv	3 200	Dielectric fluid	23 900

(2) *Water vapor*:

Water vapor is the most common greenhouse gas—it accounts for roughly 65 percent of the natural greenhouse effect. Water exists in many places on the Earth's surface—lakes, rivers, and oceans. When water heats up, it evaporates into vapor and rises from the Earth's surface into the atmosphere. It forms clouds and can act as a insulating blanket to help keep the Earth warm, or it can reflect and scatter incoming sunlight. This is why cloudy nights are warmer than clear nights. As water vapor condenses and cools, it then comes back to the Earth as snow or rain and continues on its way through the water cycle (***Casper, 2010***).

(3) *Methane* (CH_4):

Methane sources to the atmosphere generated by human activities exceed CH_4 sources from natural systems. Between 1960 and 1999, CH_4 concentrations grew an average of at least six times faster than over any 40-year period of the two millennia before 1800, despite a near-zero growth rate since 1980. The main natural source of CH_4 to the atmosphere is wetlands. Additional natural sources include termites, oceans, vegetation and CH_4 hydrates. The human activities that produce CH_4 include energy production from coal and natural gas, waste disposal in landfills, raising ruminant animals (e.g., cattle and sheep), rice agriculture and biomass burning. Once emitted, CH_4 remains in the atmosphere for approximately 8.4 years before removal, mainly by chemical oxidation in the troposphere. Minor sinks for CH_4 include uptake by soils and eventual destruction in the stratosphere (***IPCC, 2007a***).

Methane is a colorless, odorless, flammable gas formed when plants decay in an environment of very little air. It is the third-most common greenhouse gas and is created when organic matter decomposes without the presence of oxygen—a process called anaerobic decomposition. One of the most common sources is from “ruminants”—grazing animals that have multiple stomachs in which to digest their food. These include cattle, sheep, goats, camels, bison, and musk ox. In their digestive system, their large fore-stomach hosts tiny microbes that break down their food. This process creates methane gas, which is released as flatulence. Livestock also emit methane when they belch. In fact, in one day a single cow can emit one-half pound of methane into the air. Each day 1.3 billion cattle burp methane several times per minute. Humans also produce methane. Methane is also a by-product of natural gas and decomposing organic matter, such as food and vegetation. Also present in wetlands, it is commonly referred to as “swamp gas.” Since 1750, methane has doubled its concentration in the atmosphere, and it is projected to double again by 2050 (***Casper, 2010***).

Methane is the main component of natural gas. Its common name used to be marsh gas because it can be seen bubbling up from marshy areas where organic material is decomposing. Data from ice cores show that for at least 2000 years before 1800 its concentration in the atmosphere was about 700 ppb. Since then its concentration has more than doubled to a value that the ice core record shows is unprecedented over at least the last 650 000 years. During the 1980s it was increasing at about 10 ppb per year but during the 1990s the average rate of increase fell to around 5 ppb per year 11 and close to zero from 1999 to 2005. Although the concentration of methane in the atmosphere is much less than that of carbon dioxide (only 1.775 ppm in 2005 compared with about 380 ppm for carbon dioxide), its greenhouse effect is far from negligible. That is because the enhanced greenhouse effect caused by a molecule of methane is about eight times that of a molecule of carbon dioxide. The main natural source of methane is from wetlands. A variety of other sources result directly or indirectly from human activities, for instance from leakage from natural gas pipelines and from oil wells, from generation in rice paddy fields, from enteric fermentation (belching) from cattle and other livestock, from the decay of rubbish in landfill sites and from wood and peat burning. Details of estimates of the sizes of these sources during the 1990s are shown in **Table 3.13** (***Houghton, 2009***).

Table 3.13: Estimated sources and sinks of methane in millions of tonnes per year (adapted from ***Houghton, 2009***)

	Best estimate	**Uncertainty**
Sources (Natural)		
Wetlands	150	(90–240)
Termites	20	(10–50)
Ocean	15	(5–50)
Other (including hydrates)	15	(10–40)
Human-generated		
Coal mining, natural gas, petroleum industry	100	(75–110)
Rice paddies	60	(30–90)
Enteric fermentation	90	(70–115)
Waste treatment	25	(15–70)
Landfills	40	(30–70)
Biomass burning	40	(20–60)
Sinks		
Atmospheric removal	545	(450–550)
Removal by soils	30	(15–45)
Atmospheric increase	22	(35–40)

The first column of data shows the best estimate from each source
The second column illustrates the uncertainty in the estimates by giving a range of values
The figure for atmospheric increase is an average for the 1990s; note that from 1999 to 2005 the increase was close to zero.

(4) *Nitrous oxide* (N_2O):

Nitrous oxide, used as a common anaesthetic and known as laughing gas, is another minor greenhouse gas. Its concentration in the atmosphere of about 0.3 ppm is rising at about 0.25% per year and is about 16% greater than in pre-industrial times. The largest emissions to the atmosphere are associated with natural and agricultural ecosystems; those linked with human activities are probably due to increasing fertiliser use. Biomass burning and the chemical industry (for example, nylon production) also play some part. The sink of nitrous oxide is photo-dissociation in the stratosphere and reaction with electronically excited oxygen atoms, leading to an atmospheric lifetime of about 120 years (***Houghton, 2009***).

Nitrous oxide, another greenhouse gas, is released from manure and chemical fertilizers that are nitrogen-based. As the fertilizer breaks down, N_2O is released into the atmosphere. Nitrous oxide is also contained in soil by bacteria. When farmers plow the soil and disturb the surface layer, N_2O is released into the atmosphere. It is also released from catalytic converters in cars and also from the ocean. According to Hopwood and Cohen, nitrous oxide has risen more than 15 percent since 1750. Each year 7–13 million tons (6–12 million metric tons) is added to the atmosphere principally through the use of nitrogen-based fertilizers, the disposal of human and animal waste in sewage treatment plants, automobile exhaust, and other sources that have not been identified yet. The use of nitrogen-based fertilizers has doubled in the last 15 years. Although good for the productivity of crops, they break down in the soil and release N_2O into the atmosphere (***Casper, 2010***).

(5) *Chlorofluorocarbons* (CFCs):

Halocarbons include the fluorocarbons, methylhalides, carbon tetrachloride (CCl_4), carbon tetrafluoride (CF_4), and halons. They are all considered to be powerful greenhouse gases because they strongly absorb terrestrial infrared radiation and stay in the atmosphere for many decades. Fluorocarbons are a group of synthetic organic compounds that contain fluorine and carbon. A common compound is chlorofluorocarbon (CFC). These classes contain chlorine atoms and have been used in industry as refrigerants, cleaning solvents, and propellants in spray cans. These fluorocarbons are harmful to the atmosphere, however, because they deplete the ozone layer; their use has been banned in most areas of the world, including the United States. Hydrofluorocarbons (HFCs) contain fluorine and do not damage the ozone layer. Fluorocarbon polymers are chemically inert and electrically insulating. They are used in place of CFCs because they do not harm or break down ozone molecules, but they do trap heat in the atmosphere. HFCs are used in air conditioners and refrigerators. The best way to keep HFCs out of the atmosphere is to recycle the coolant from the equipment they are used in. Fluorocarbons have several practical uses. They are used in anesthetics in surgery, as coolants in refrigerators, as industrial solvents, as lubricants, water repellents, stain repellents, and chemical reagents. They are used to manufacture fishing line and are contained in products such as Gore-Tex and Teflon (***Casper, 2010***).

The CFCs are man-made chemicals which, because they vaporize just below room temperature and because they are non-toxic and non-flammable, appear to be ideal for use in refrigerators, the manufacture of insulation and aerosol spray cans. Since they are so chemically un-reactive, once they are released into the atmosphere they remain for a long time – 100 or 200 years – before being destroyed. As their use increased rapidly through the 1980s their concentration in the atmosphere has been building up so that they are now present (adding together all the different CFCs) in about l ppb (part per thousand million – or billion – by volume). This may not sound very much, but it is quite enough to cause two serious environmental problems.

(6) *Ozone* (O_3):

The word ‘ozone’ comes from the Greek word ‘ozein’ which means ‘to smell’. This meaning comes from ozone at the ground level, which gives off a pungent, acrid odor. This meaning clearly reflects the problem of ozone in the lower atmosphere. However, ozone is also present in the stratosphere. The stratosphere is a region roughly ten to fifty kilometers above the Earth’s surface, which exists above the planetary boundary layer. This layer absorbs the middle portion of the Ultra Violet (UV) spectrum. Ozone absorbs all UV radiation with wavelengths shorter than about 290 nanometers (UV-C), most of it in the 290 to 320 nanometers range (UV-B) and little above 320 nanometer (UV-A). While UV-A is relatively innocuous, UV-C is lethal and UV-B is harmful to many life forms.2 Due to the fact that oxygen and other gases absorb wavelengths only below 200 nanometers, the ozone is our sole defense against the middle ultraviolet (***Gillespie, 2006***).

The maximum ozone concentration, occurring between twenty and thirty kilometers above the Earth, is only a few parts per million. Since air at that altitude is about 5% as dense as at ground level, the sparse concentrations of ozone are more aptly described as a veil than as a layer. The measurement of the ozone is done in ‘Dobson units’ (‘DUs’). The DU provides a convenient way of expressing what the total thickness of the ozone layer would be if measured at sea-level. One DU is equal to a thousandth of a centimetre at standard temperature and pressure. A hundred DUs is equivalent to a layer of ozone that, at the temperature and pressure found at the Earth’s atmosphere, would be 1 millimetre thick. Three hundred DUs (the average for the globe) corresponds to the abundance of molecules that would form a layer just 3 mm thick at sea level, with the weight of the atmosphere compressing it. The normal amount of ozone over Antarctica is about 400 DUs in summer and 300 in late winter/early (***Gillespie, 2006***).

Ozone (O_3) is regarded as one of the most damaging air pollutants to which plants are exposed. Over large rural areas of industrialized countries, its average monthly concentration increased during the last century to between 20 and 80 ppb. During episodes of severe air pollution, concentrations as high as 400 to 500 ppb have been monitored. Ozone is a secondary pollutant resulting from photochemical reactions (mainly volatile organic compounds and nitrogen oxides). Under favorable meteorological conditions, ozone may accumulate in the troposphere and reach a level that causes significant decrease in growth and yield of ozone-sensitive species in many parts of the world. The problem of phytotoxicity is well established in Europe and North America. More recently, high concentrations of ozone have also been measured (***Wahid et al. 1995***).

Ozone enters the leaves through the stomata and diffuses within the apoplast. In this microenvironment it is intensively reactive and produces high levels of toxic compounds such as hydroxyl and superoxide radicals, hydrogen peroxide and other reactive oxygen species. These active oxygen species react with proteins, lipids, and plasma membrane. Antioxidative defense activity systems may prevent this damage. Impact on plant crop yield ranges from minimal visible symptoms to substantial inhibition of productivity, including reduced photosynthetic capacity, enhanced rate of maintained respiration, and increased retention of fixed carbon in source leaves. These plant responses can affect the plants’ abilities to respond to further stress attacks. The action of ambient O_3 on the plant defense system enhances attack by pathogens but may lead to induce resistance. In addition, the impact of O_3 is profoundly influenced by other environmental factors.

The effect of O_3 on photosynthesis interacts with elevated CO_2. Therefore, elevated O_3 determines the magnitude of the yield-enhancement by elevated CO_2. The relative yield stimulation by elevated CO_2 is larger in an atmosphere containing elevated levels of O_3, or vice versa, in a CO_2-enriched atmosphere, negative effects of O_3 are less than at ambient CO_2. This was observed, for instance, in soybean, cotton, and winter wheat, but not in clover. The protective effect of elevated CO_2 under O_3 stress could be explained by a reduction in leaf conductance which reduces O_3 uptake, or an increase in the activity of anti-oxidant enzymes. But most current evidence suggests that the protection from O_3 in a CO_2-rich atmosphere is primarily due to O_3 exclusion, rather than an increased detoxification capacity. This is in agreement with the observation that O_3 flux to the plasmalemma in wheat and barley is controlled by stomata rather than by direct reaction of O_3 with detoxifying substances such as cell wall ascorbate (***Gillespie, 2006***).

Global climate change, increasing CO_2, and regional O_3 pollution are three important aspects of the changing atmosphere with pronounced effects on all agricultural ecosystems, but the exact outcome of the interactive effects cannot be predicted in any generalized way. Information gained from experiments with a single factor have little predictive value because in reality, variable combinations of limiting factors, differing in their temporal and spatial variability, are interacting, and ecosystem responses to interacting global changes may differ greatly from simple combinations of single-factor responses (***Shaw et al. 2002***).

The situation is even more complicated when plant–plant interactions or feedbacks operating through the soil are considered. It could be suggested that many of the beneficial effects of elevated CO_2, including higher yield, improved resource-use efficiency, reduced susceptibility to some fungal pathogens, or increased O_3 tolerance could be reduced or even lost in a warmer world. There is also emerging evidence that in some grassland ecosystems elevated CO_2 may suppress the positive effects of increasing temperature and resource availability on productivity. Effects of a gradual change in climate may develop slowly and may not be noticeable against the background of impacts of natural multi-decadal climate variability. Also, much larger socio-economic effects in the agricultural sector of individual countries may mask any influence of a slowly developing transient climatic change, and modern societies are able to make technological and economic adjustments. However, climate change is likely to depress crop yields especially in food-insecure regions, and increased climate variability further increases the risks to future food production. Because the potential for adaptations may be much smaller in less-developed regions and in regions where agricultural intensity declines due to socio-economic constraints, effects of global climate change and regional air pollution are likely to become more severe (***Gillespie, 2006***).

Overlapping Climate Change Gases

A number of gases which influence other international environmental problems also contribute to ozone depletion. Although the air pollutants of aerosols, sulphate particles and carbon monoxide all contribute to ozone depletion, the main pollutants which have a strong influence are related to climate change. Thus, as the 1985 Vienna Convention recognized, CO_2 was a chemical which, ‘affects stratospheric ozone by influencing the thermal structure of the atmosphere’. The influence upon the thermal structure relates to the general idea of global warming, or more specifically, ‘increasing concentrations of CO_2 should decrease the temperature of the stratosphere, altering rates for several key reactions, resulting in a change in ozone’. The basic theory that warming in the troposphere will result in cooling in the stratosphere has remained largely unchallenged. However, the influence that this will have upon the ozone layer has been the subject of debate. Originally, it was assumed that cooling in the stratosphere, caused by global warming, could off-set the destruction of the ozone layer. This cooling was believed to enhance natural chemical reactions which stimulate the manufacture of ozone. However, by 1989, this view was challenged with the currently prevailing theory that a cooler stratosphere was not beneficial for the protection of the ozone layer as it would be catalytic for its accelerated, prolonged destruction. In addition to the above generic problems associated with a general warming, there are also two key climate change gases, CH_4 and NO_x, which play additional roles in ozone destruction. The projected increases in these gases are predicted to have small chemical effects on the rate of increase of the total global column of ozone in the next fifty year. However, this could become more significant later in the 21^{st} century (***Gillespie, 2006***).

4 *The Nile and Climate Changes: A Case Study for Egypt*

Knowing is not enough, we must apply.
Willing is not enough, we must do.
Johan Wolfgang von Goethe, 1749–1832

4. *The Nile and Climate Changes: A Case Study for Egypt*

4.1 *Introduction*

Nile, the longest river of the world (ca 6,800 km) and its basin (2.9×10^6 km^2), including its various "source" lakes, some brief notes on its main neighbors (Congo and Logone-Chari) and their history are given (***Ibrahim, 1984; Said, 1981***). The biota of the basin is moderately diverse, and endemism tends to be low, except in some of the "old" source lakes. The situation is complicated by the fact that at least two of these lakes (Victoria and Tana) dried out around or slightly before the beginning of the Holocene, and thereafter, speciation (especially of cichlid fish) may have happened at an unusually great speed. In general, the Nile offers a pathway for African species to extend from the tropics to a Mediterranean climate and spill over into the Levant and Arabia. Such incursions may have happened many times across history, with some of the older "waves" using the Red Sea (before its opening to the Indian Ocean) rather than the Nile (***Dumont, 2009***).

The Main Nile receives its water from two main sources: the Ethiopian Highlands and the Equatorial Plateau. The Ethiopian tributaries include the Blue Nile and the Atbara. In addition to Ethiopia, the catchment area includes western Eritrea. The equatorial catchment area includes Western Kenya, Uganda, Rwanda, Burundi, as well as the Central African Republic, the Republic of the Congo and the Democratic Republic of the Congo. One of the most salient features of the Nile is its summer flood. Around mid-July, water, mostly from Ethiopia, begins to reach Egypt. By the middle of August, the inundation reaches its peak. For approximately three weeks the Nile level remains stationary. In October it may rise again, but by the end of October the inundation wanes and water begins to subside. The rise of flood water from May to September may reach as much as 7m. By May, the Nile sinks to its lowest level. Fluctuations of Nile flood discharge during the period from the 7^{th} to the 15^{th} century AD are documented in historical measurements of Nile flood levels, at the Roda Nilometer, opposite Old Cairo, taken twice a year—one when the Nile was at its lowest point and the other when it reached its peak (***Hassan, 2007***).

Since early pharaonic times, man has interfered with the river and its flow regime, in an effort to control the yearly "flood of a hundred days", but large-scale damming only started in the nineteenth century, and culminated with the construction of the Aswan High Dam in the 1960s, reducing the river to a giant irrigation canal. More recent developments include the construction of the Toshka lakes diverticle to Lake Nasser, a project with an uncertain future. The Nile is a river rich in human history, which includes an ancient civilization and achievements of geographical exploration. Accounts of these are numerous, but there appears to be no general summary–history of scientific research on the river itself. The following outline has emphasis upon hydrobiology and its physical and chemical background. References are given only as *examples*; naturally they postdate the time that the actual work was done (***Dumont, 2009***).

The Nile monograph by **Rzóska (1976)** was entitled "biology of an ancient river". Whether the Nile is indeed an ancient river is, however, a matter of taste. Rather, one could conceive the Nile as a puzzle, to which at times pieces were added, while at other times pieces were subtracted. This happened all along its history, including the late Pleistocene. In its present form, the delta, for example, is not much more than 6,000 years old. On the other hand, surely a river (or a series of consecutive rivers) existed in North-East Africa since it emerged from the Tethys Sea at the end of the Mesozoicum. **Talbot & Williams and Williams & Talbot (2009)** summarize the current views on the various stages of the drainage systems that ultimately became the Nile as we know it. As usual, we know more as we approach the present, and the Pleistocene history of the River is, in broad lines, well established even if some parts of the basin (e.g. the evacuation pathway of the Blue Nile across geological time) still invites more research work (***Talbot and Williams; Williams and Talbot, 2009***). The twentieth century stood witness to the progressive, and ultimately, the complete regulation of the Nile. Population growth and economic expansion, especially in the lower Nile valley, continue to increase the demand on the water resource, a process that has been underway for about five millennia, but risks to reach a climax soon. The river is therefore more than a complex ecological jewel: it is a multi-purpose renewable resource that should be wisely managed, however difficult this may be (***Dumont, 2009***).

The nineteenth century quest for the source(s) of the Nile is a heroic chapter in the history of the exploration of the African continent, and it was long thought that Lake Victoria was its ultimate source. Yet, that lake itself is fed by rivers that arise further south, the most important of which is the Kagera. Until recently, it was believed that its tributary, the Luvironza, that springs in Tanzania at ca 4° S, was the Nile's ultimate "source". However, a revised length estimate of 6,718 km was established in 2006, when a British–New Zealand expedition found that the tributary of the Kagera River arising furthest to the south is the Rukarara. It springs in the Nyungwe forest, Rwanda. The Nile is the only permanent river that manages to cross the Sahara, the largest desert in the world, and reach the Mediterranean Sea, yet its early beginnings are in a montane equatorial climate, and it traverses a series of climatic zones before reaching its delta. Its basin orientation is unique among the major rivers in the world in that it runs almost perfectly from south to north, discharging at 31° N. Each climate zone which it crosses shows considerable variability in precipitation and run-off (***Camberlin, 2009***), but over more than half its length it receives less than 150 mm of rain per annum. Its basin is relatively narrow and small (2.9×10^6 km^2) compared to that of most other large rivers of the world (the Congo, ca 4×10^6 km^2 according to **Bailey, 1986**; the Amazon, ca 7×10^6 km^2 according to ***Sioli, 1984***).

The Nile basin covers the whole of Egypt and the Sudan, except for the short rivers that drain the Red Sea Hills towards the Red Sea. Most of these are wadis that only discharge water for few days after rare desert rains. For both countries, the Nile is a vital economic resource and the need to secure access to sufficient water has dominated their political agenda since times immemorial (***Allan, 2009***). The basin also covers about one third of Ethiopia (***Tudorancea & Taylor, 2002***), the whole of Uganda, and part of Kenya, Tanzania, Congo, Rwanda and Burundi. Conventionally, the Nile is divided into a number of sub-basins: the White or Equatorial Nile and its source lakes, the Blue Nile and Lake Tana, and the Main Nile. The River Atbara is often considered a separate, although small, sub-basin. Presently not or hardly active is the so-called Yellow or Desert Nile, comprised of the valleys of the Wadi Howar and the Wadi El Milk. Around 6,000 BP, these watercourses significantly augmented the total discharge with water coming from the Nile-Chad divide (Jebel Marra, the Tabago and Meidob hills, and the Eastern Ennedi) (***Kuper and Kroepelin, 2006; Dumont, 2009***).

The entire White Nile sub-basin has a surface area of ca 3.8×10^5 km^2. It is best known for the large, reputedly ancient lakes on the plateau in the south of its drainage area. Of these, Lake Victoria is the largest. With a surface area of 7×10^4 km^2, it is second in size only to the Caspian Lake in West Asia and Lake Superior in North America (***Lehman, 2009***). The White Nile also drains a sizeable part of the Western Rift, including lakes Albert and Edward (***Green, 2009***). Both obtain much of their water from the high mountains of the Rwenzori (***Eggermont et al. 2009***). A second source of water is the Virunga highlands, which rose as a volcanic plug across the rift valley between 9 and less than 3 million years ago (***Kampunzu et al. 1998***). This deleted Lake Kivu from the Nile basin. The Virunga volcanoes also blocked the course of a number of smaller rivers (***Beadle, 1981***), and created the Kigezi lakes to the north. They are renowned for their scenic beauty, but are also of great biological interest (***Green, 2009***). The outflow of these lakes eventually finds its way to either Lake Victoria or Lakes Albert-Edward (***Dumont, 2009***).

The freshwater used in fully irrigated agriculture (or in supplementary irrigation crops and fodder production), on the other hand, is also significant – particularly for the Sudan and Egypt. First use and subsequent re-use of freshwater in irrigated farming accounts for about 90% of the freshwater use in the Nile river system (***Wichelns, 2001***). As we shall see, very little of the blue water used for food production is ‘exported’ in the form of crops or livestock back up to the headwater states. More significant amounts (approximately 250 Mm^3 yr^{-1}) are used to grow citrus and vegetables destined for European supermarket shelves. To appreciate the importance of such flows on the water resources of the basin, it is useful to consider the basin’s ‘renewable water potential’. The record of flows of the Nile has been kept for an astounding number of centuries (***Tvedt, 2004***). But as evapotranspiration rates, freshwater use and return flows are all known very imprecisely, any estimate of the renewable potential is necessarily inaccurate.

Table 4.1 shows that the Nile River as a whole has an annual flow of roughly 100,000 $Mm^3\ yr^{-1}$ (***Zeitoun et al. 2010***). The estimated total amount of soil water used in production of crops, based on the analysis presented later, is about 229,000 $Mm^3\ yr^{-1}$ (not including the unspecified amount of soil water consumed by natural vegetation) (***FAO, 2006***). Of course the shares of water stored in the soil or running through the river vary considerably from year to year, as a function of the high variability between wet or dry years (***Conway et al. 2007***).

Table 4.1: Freshwater resources of the Nile (adapted from ***Zeitoun et al. 2010***)

Country	Average annual precipitation (mm)	Nile River freshwater flows[a]		Soil water consumption (for agriculture) ($Mm^3\ yr^{-1}$)	Groundwater production ($Mm^3\ yr^{-1}$)
		Inflow ($Mm^3\ yr^{-1}$)	***Outflow*** ($Mm^3\ yr^{-1}$)		
DR Congo	1245	0	1500	31,909	421,000
Burundi	1110	0	1500	6132	2100
Rwanda	1105	1500	7000	11,000	3600
Tanzania	1015	7000	10,700	31,583	30,000
Kenya	1260	0	8400	20,386	3000
Uganda	1140	28,700	37,000	45,804	29,000
Eritrea	520	0	2200	843	–
Ethiopia	1125	0	80,100	31,075	40,000
Sudan	500	117,100	55,500	50,313	7000
Egypt	15	55,500	<10,000 (to sea)	0	13,000
Total in system		approx. 229,000		approx. 100,000	

[a] Evaporation from natural and constructed storage not accounted.

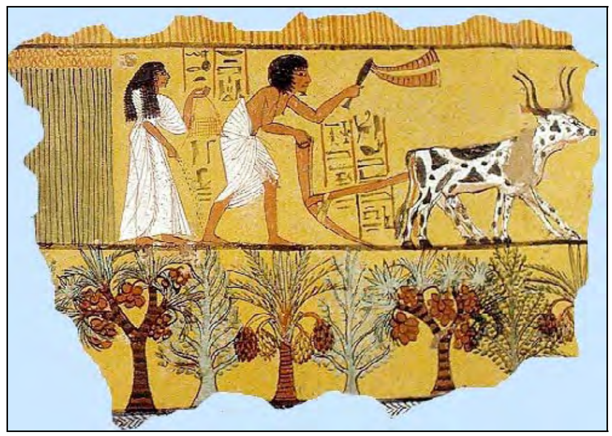
This chapter is especially focused on Egypt, as a case study, and the relationship between the Nile and climate changes. This introductory chapter describes some of the Nile basin-related global climate changes including the following items: Nile basin climates, climate changes and global water scarcity, impacts on Nile flows, and finally, climate variability and changes in the Nile basin.

4.2 *Egypt: the Gem of the World*

Egypt, officially the **Arab Republic of Egypt**, is a country mainly in North Africa, with the Sinai Peninsula forming a land bridge in Southwest Asia. Egypt is thus a transcontinental country, and a major power in Africa, the Mediterranean Basin, the Middle East and the Muslim world. Covering an area of about 1,010,000 square kilometers (390,000 sq mi), Egypt is bordered by the Mediterranean Sea to the north, the Gaza Strip, the Red Sea to the east, Sudan to the south and Libya to the west. Egypt is one of the most populous countries in Africa and the Middle East. The great majority of its over 81 million people live near the banks of the Nile River, in an area of about 40,000 square kilometers (15,000 sq mi), where the only arable land is found (2011). The large areas of the Sahara Desert are sparsely inhabited. About half of Egypt's residents live in urban areas, with most spread across the densely populated centres of greater Cairo, Alexandria and other major cities in the Nile Delta.

Monuments in Egypt such as the Giza pyramid complex and its Great Sphinx were constructed by its ancient civilization. Its ancient ruins, such as those of Memphis, Thebes, and Karnak and the Valley of the Kings outside Luxor, are a significant focus of archaeological study. The tourism industry and the Red Sea Riviera employ about 12% of Egypt's workforce. The economy of Egypt is one of the most diversified in the Middle East, with sectors such as tourism, agriculture, industry and service at almost equal production levels.

Egyptian farming



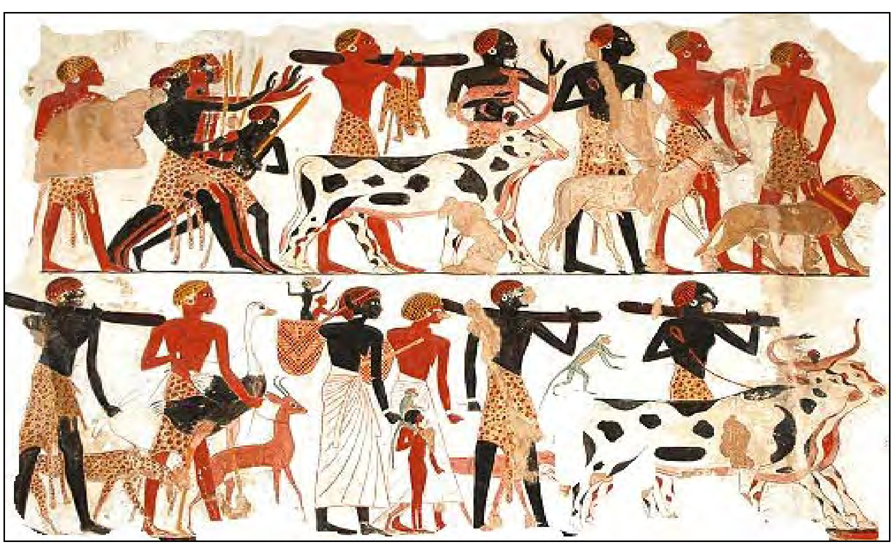
Harvesting

Shaduf (for irrigation)

Plough (using farming animal)

2011 Revolution

On 25 January 2011, widespread protests began against Mubarak's regime. The objective of the protest was the removal of Mubarak from power. These took the form of an intensive campaign of civil resistance supported by a very large number of people and mainly consisting of continuous mass demonstrations. By 29 January it was becoming clear that Mubarak's regime had lost control when a curfew order was ignored, and the army took a semi-neutral stance on enforcing the curfew decree. Some protesters, a very small minority in Cairo, expressed nationalistic views against what they deemed was foreign interference, highlighted by the then-held view that the U.S. administration had failed to take sides. On 11 February 2011, Mubarak resigned and fled Cairo. Vice President Omar Suleiman announced that Mubarak had stepped down and that the Egyptian military would assume control of the nation's affairs in the short term. Jubilant celebrations broke out in Tahrir Square at the news. Mubarak may have left Cairo for Sharm El-Sheikh the previous night, before or shortly after the airing of a taped speech in which Mubarak vowed he would not step down or leave. On 13 February 2011, the high level military command of Egypt announced that both the constitution and the parliament of Egypt had been dissolved. The parliamentary election was to be held in September. A constitutional referendum was held on 19 March 2011. On 28 Nov 2011, Egypt held its first parliamentary election since the previous regime had been in power. Turnout was high and there were no reports of irregularities or violence, although members of some parties broke the ban on campaigning at polling places by handing out pamphlets and banners (www.answers.com/8.1.2012).



Egyptian painting

Egypt is the gift of the Nile

The Greek historian, ***Herodotus***, coined the phrase that '***Egypt was the gift of the Nile***', in his 'An Account of Egypt: Being the Second Book of His Histories Called Euterpe'. Herodotus of Halicarnassus was a Greek historian who lived in the 5th century BC (c. 484 BC-c. 425 BC) and is regarded as the "*Father of History*" in Western culture. He is cited as writing - That of the Nile "the river rises of itself, waters the fields, and then sinks back again - thereupon each man sows his field and waits for the harvest." This was obviously referring to the annual flood. He also described Egypt as "A land won by the Egyptians and given them by the Nile." So Egypt was the Nile River's gift - because without the Nile there would be no Egypt only desert. So anything derived from the Nile would also be looked upon as a gift - the water, the floods fertile soil, the fish and the rivers obvious use for transport etc. Herodotus said "*Egypt is the gift of the Nile*" admiring the Nile river as God's gift for the Egyptian people, as without the Nile river; Egypt would have been desert. The Nile was the lifeblood of Egypt. Their civilization depended on it. Egypt was a glorious civilization, which contributed in many ways to two modern-day civilizations: the West and the Middle East. So, in a sense, the Nile "gave" us (meaning the West & Middle East) the gift that was/is Egypt (http://answers.yahoo.com/9.1.2012).

Egypt is one of the oldest continuously settled lands in the world. Egyptians, except for a few Nubians, speak Arabic. About 90 percent of the people are Muslim, and Islam is the state religion. The Copts are the largest non-Muslim religious group. Estimates of their numbers vary between six million and nine million. Half of the Egyptian people are under twenty years of age; two-thirds are under thirty. The number of dependent children supported by working adults is high, a situation that severely strains the economy. Egypt's government and economy are increasingly unable to meet the demands for food, shelter, education, and jobs. Some three million Egyptians have migrated to other Arab countries, particularly the oil-producing states, in search of work. Their remittances to their families constitute a major source of Egypt's hard currency and help to offset the difference between the country's imports and exports.

Climate

The climate of Egypt is characterized by a hot season from May to September and a cool season from November to March. Extreme temperatures during both seasons are moderated by the prevailing northern winds. In the coastal regions average annual temperatures range from a maximum of 37°C (99°F) to a minimum of 14°C (57°F). Wide variations of temperature occur in the deserts, ranging from a maximum of 46°C (114°F) during daylight hours to a minimum of

6°C (42°F) during the night. During the winter season desert nighttime temperatures often drop to 0°C (32°F). The most humid area is along the Mediterranean coast, where the average annual rainfall is about 200 mm (about 8 in). Precipitation decreases rapidly to the south; Cairo receives on average only 25 mm (1 in) of rain a year, and in many desert locations it may rain only once in several years (***Goldschmidt et al. 2006***).

The topography of the delta varies from about 200 m elevation at Cairo at the apex of the delta to near zero on the Mediterranean some 200 kilometers to the north. The northern region of the delta hosts several important lakes such as Lake Maryut, Lake Edku, Lake Brullus and Lake Manzala. The wet lands of northern Egypt constitute about 25 % of the total wetland of the Mediterranean and provide over 66 % of the fish catch of the country. The topography of the northern coast is highly variable. **Figure 4.1** shows the topography of Egypt (***El Raey, 2011***).

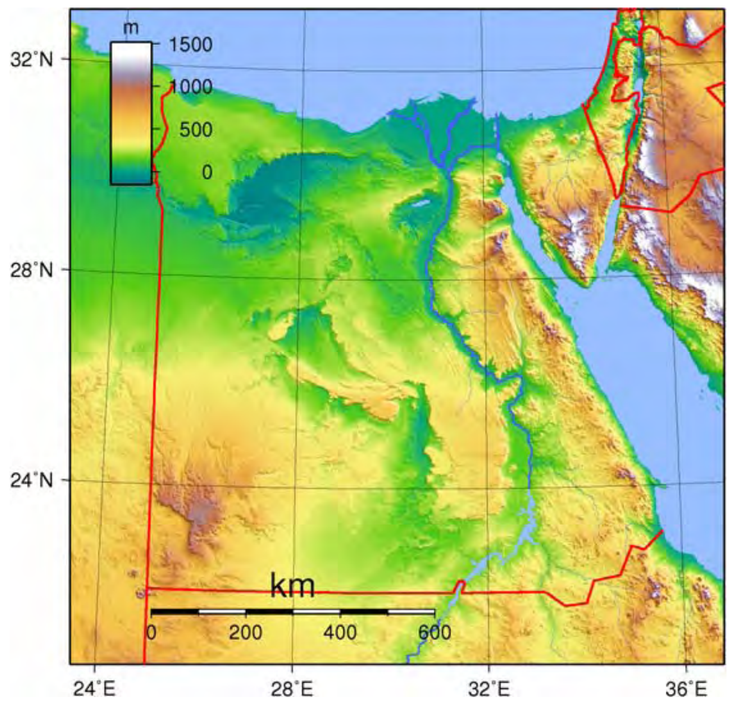


Figure 4.1: Topography of Egypt (www.answers.com/9.1.2012)

Geography of Egypt

The geography of Egypt relates to two regions: Southwest Asia and North Africa. Egypt has coastlines on both the Mediterranean Sea and the Red Sea. Covering 1,001,449 km^2, Egypt has a land area about the same as that of Texas and New Mexico combined, four times bigger than that of the United Kingdom, and twice as big as that of France. The longest straight-line distance in Egypt from north to south is 1,024 km, while that from east to west measures 1,240 km. More than 2,900 km of coastline on the Mediterranean Sea, the Gulf of Suez, the Gulf of

Aqaba and the Red Sea constitute Egypt's maritime boundaries. So, Egypt is the gem of the world (**Figure 4.2**).

Figure 4.2: Map of Egypt

4.3 *The Nile and Water Scarcity*

The use of water for agricultural production in water scarcity regions requires innovative and sustainable research, and an appropriate transfer of technologies. Water is becoming scarce not only in arid and drought prone areas but also in regions where rainfall is abundant: water scarcity concerns the quantity of resource available and the quality of the water because degraded water resources become unavailable for more stringent requirements. The sustainable use of water—resource conservation, environmental friendliness, appropriateness of technologies, economic viability, and social acceptability of development issues—is a priority for agriculture in water scarce regions. Imbalances between availability and demand, degradation of surface and groundwater quality, intersectorial competition, inter-regional and international conflicts, often occur in these regions. Innovations are, therefore, required mainly relative to irrigation management and practice since the agriculture sector is far ahead in demand for water in those regions. Policies and practices of irrigation water management under water scarcity must focus on specific objectives according to the causes of water scarcity. Valuing the water as an economic, marketable good may be insufficient since water acts not only for producing but is also supporting other natural resources. A coupled environmental, economic, and social approach is required in valuing the water, while an integrated technical and scientific approach is essential to develop and implement the management practices appropriate to deal with water scarcity (***Pereira et al. 2002***).

Water scarcity definition:

Water scarcity is among the main problems to be faced by many societies and the World in the 21st century. *Water scarcity* is commonly defined as a situation when water availability in a country or in a region is below 1000 m^3/person/year. However, many regions in the World experience much more severe scarcity, living with less than 500 m^3/person/year, which could be considered severe water scarcity. The threshold of 2000 m^3/person/year is considered to indicate that a region is water stressed since under these conditions populations face very large problems when a drought occurs or when man-made water shortages are created. However, the concept of water availability based on indicators driven from the renewable water resources divided by the total population should be taken with great care. It is often the case that the renewable resource is augmented by desalination, non-renewable groundwater resources and waste water re-use to compensate for their renewable water scarcity. Where there is little opportunity for irrigation, smaller per capita volumes may be adequate. In these cases a simple volume per person of renewable water may not be a good indicator of adequacy of supply (***Pereira et al. 2009***).

In most of the world’s watercourses, dramatic modifications have occurred as a consequence of intensive use by human societies. The simplification of the channel network and the alteration of water fluxes have an impact upon the capacity of fluvial systems to recover from disturbances, because of their irreversible consequences. However, human impacts on river hydrology, such as those that derive from regulating their flow or by affecting their channel geomorphology, affect the functional organization of streams, as well as the ecosystem services that derive from them, and lead to the simplification and impoverishment of these ecosystems. Pollution, water abstraction, riparian simplification, bank alteration, straightening of watercourses, dam construction, and species introduction are widespread perturbations in river ecosystems. These human-driven alterations are part of global changes. The simplification of the channel network and the alteration of water fluxes reduce the capacity of fluvial systems to recover from natural disturbances. Hydrologic alterations affect the functional organization of streams and rivers, and lead to a simplification and impoverishment of the biota within these ecosystems (***Sabater and Tockner, 2010***).

Water scarcity causes enormous problems for the populations and societies. The available water is not sufficient for the production of food and for alleviating hunger and poverty in these regions, where quite often the population growth is larger than the capability for a sustainable use of the natural resources. The lack of water does not allow industrial, urban and tourism development to proceed without restrictions on water uses and allocation policies for other user sectors, particularly agriculture. Natural fresh water bodies have limited capacity to respond to increased demands and to receive the pollutant charges of the effluents from expanding urban, industrial and agricultural uses. In regions of water scarcity the water resources are often already degraded, or subjected to processes of degradation in both quantity and quality, which adds to the shortage of water. Health problems are commonly associated with scarcity, not only because the deterioration of the groundwater and surface waters favours water borne diseases, but because poverty makes it difficult to develop proper water distribution and sewerage systems. Water conflicts still arise in water stressed areas among local communities and between countries since sharing a very limited and essential resource is extremely difficult despite legal agreements. Poverty associated with water scarcity generates migratory fluxes of populations within countries or to other countries where people hope to have a better life, but where they may not be well received. Last, but not least, water for nature has become a low or very low priority in water stressed zones. Preserving natural ecosystems is often considered a superfluous use of water compared with other uses that directly relate to healthy human life, such as domestic and urban uses, or that may lead to the alleviation of poverty and hunger, such as uses in industry, energy and food production. However, the understanding that natural ecosystems, namely the respective genetic resources, are useful for society is growing, and an effort to protect reserve areas is already developing, even in water scarce regions (***Pereira et al. 2009***; **Figure 4.3**).

Regions where water has been always scarce gave birth to civilizations that have been able to cope with water scarcity. These societies developed organizational and institutional solutions and water technologies and management skills within the local cultural environment that allowed for appropriate water for domestic use, food production and local industrial purposes. Lifestyle and development changes during the last decades created new needs for water, provided contradictory expectations on cultural and institutional issues, and led to very strong increases on the demand for water. The existing balances among demand and supply were broken and new equilibriums are required, mainly through the use of modern technologies and management tools which must be adapted to the local culture, environment, and institutions. Finding such new equilibriums is the challenge for the societies living in water stressed areas, and for professionals in a multitude of scientific and technological domains which impinge on the cultural, social and environmental facets of water resources (***Pereira et al. 2009***).

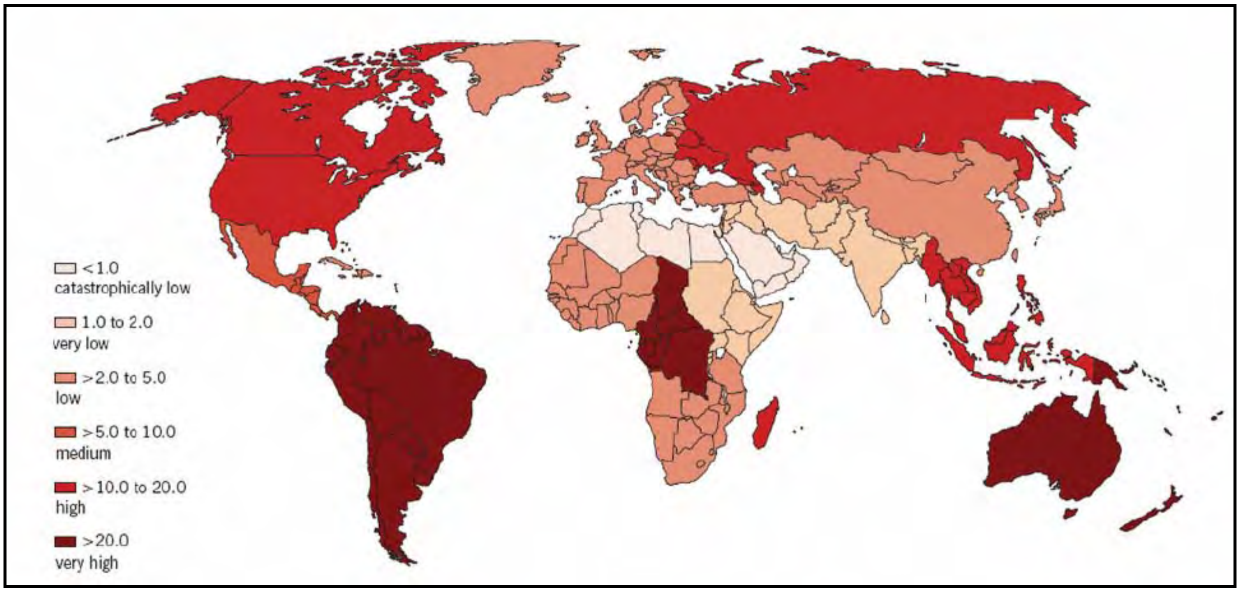


Figure 4.3: World water availability per capita (1000 m^3/year) and per country (from ***UNEP, 2002***)

There is much talk of a water crisis, of which the most obvious manifestation is that 1.2 billion people lack access to safe and affordable water for their domestic use. Less well documented is that a large part of the 900 million people in rural areas that have an income below the one-dollar-per-day poverty line lack access to water for their livelihoods. The lack of access to water has major impacts on people's well-being. Lack of access to safe drinking water and sanitation, combined with poor personal hygiene, causes massive health impacts, particularly through diarrhoeal diseases, estimated to cost the lives of 2.18 million people, three-quarters of whom are children younger than 5 years old, annually, and an annual global burden of disease measured as 82 million disability adjusted life years. The poorest of the poor are also most affected by lack of access to water for productive purposes, resulting in a vicious cycle of malnutrition, poverty and ill health. Fresh water is critical to an array of global challenges from health, to malnutrition, poverty, and sustainable natural resources management (***Rijsberman, 2006***).

What is water scarcity? When an individual does not have access to safe and affordable water to satisfy her or his needs for drinking, washing or their livelihoods we call that person water insecure. When a large number of people in an area are water insecure for a significant period of time, then we can call that area water scarce. It is important to note, however, that there is no commonly accepted definition of water scarcity. Whether an area qualifies as ‘‘water scarce’’ depends on, for instance: (a) how people’s needs are defined— and whether the needs of the environment, the water for nature, are taken into account in that definition; (b) what fraction of the resource is made available, or could be made available, to satisfy these needs; (c) the temporal and spatial scales used to define scarcity. Water is a very complex resource. Contrary to a static resource such as land, water occurs in a very dynamic cycle of rain, runoff and evaporation, with enormous temporal and spatial variations as well as variations in quality that completely govern its value to people and ecosystems. That water can be a nuisance (in floods) as well as a lifesaving resource (in droughts) is obvious, but that both conditions can occur in one location within a single year is more surprising. Annual average water availability in such a situation has little meaning to measure water scarcity. Large parts of monsoon Asia suffer from severe water scarcity while the average annual resource availability appears to be plentiful. Is there not enough or too much? If we build a dam to capture the flood water, prevent flood damage and make the excess water available during the dry period, then the place may no longer suffer from floods or droughts—the dam affects the water scarcity we measure and the existence of water infrastructure should therefore be accounted for in an analysis of water scarcity. Spatial scales also impact the measures of water scarcity (***Rijsberman, 2006***).

A subsequent consequence of altered hydrological conditions is the export of solutes, as well as changes of the biogeochemical processes (**Table 4.2**) that derive from drought and rewetting.

Table 4.2: Summary of effects caused by water scarcity (adapted from ***Sabater and Tockner, 2010***)

Water quality descriptor	Effect o f low flow	Effect on biota	Affected process
Temperature	Lower oxygen content Higher metabolic rates Combined effects with toxicants and nutrients	Invertebrates Fish All groups All groups	Decrease in oxygen availability Higher primary production Higher respiration rates General effects on structure and metabolism
Conductivity	Enhanced water salinity	All groups	Physiological regulation Changes in community composition
Organic matter	Accumulation of organic matter	Bacteria Primary producers	Slowed down decomposition? High oxygen consumption High mineralization
Sediments	Siltation	Primary producers Invertebrates Fish	Reduced production Changes in community composition Difficulties in gas diffusion
Nutrient	Higher concentration; eutrophication	Primary producers Potential bottom up-effects	Higher gross primary production Lower efficiency on materials processing
Pollutants	Increase of pollutant concentration and enhanced effects on the biota	All groups Complex food web effects	Diversity decrease? Effects on metabolism Effects on material processing

The physical characteristics and processes leading to water scarcity complement the discussion of concepts. Climatic conditions dominant in water scarce regions are analyzed, particularly rainfall variability and evaporation. The essential hydrologic characteristics are briefly considered, referring to the runoff regimes prevailing in water stressed regions, the processes affecting groundwater recharge and availability, and sediment loads and water quality, including those aspects leading to desertification and water-shortage. Special reference is made to droughts, particularly concerning definitions and the possibilities of forecasting. Also included are references to the need for data collection, data quality assessment and use of data handling and archiving techniques so that data are readily available for planning and management studies. The impacts of droughts and desertification in many semi-arid and sub-humid areas are growing and the importance of respective processes is receiving increased consideration. Therefore, an in-depth examination of drought concepts, identification indices, prediction, and forecasting is produced as well as revisiting monitoring and risk management tools. Desertification concepts, indicators, and monitoring and information tools are also dealt in the perspective of supporting the identification of vulnerability domains and measures and practices that may combat desertification. There is also an in-depth examination of conceptual thinking in coping with water scarcity. This is oriented to provide a basis for innovation in examining the value of water in conditions of water scarcity, to encourage different thinking in assessment of the social, environmental and economic values of water and to consequently establish appropriate priorities for water allocation and use, taking such values into account (**Figures 4.4, 4.5, 4.6, and 4.7; *Pereira et al. 2009***).

According to **Tawfik, (2009**), the Nile is the main source of drinking water in Egypt. Over 85% of the country's water is consumed annually by irrigation. Hence, safe water will provide pollutant-free agricultural products and production will increase as well. The concentration of organic material decreased 15–69% in the main course, dissolved salts decreased 1.5–2.0%, while phosphate concentration decreased 14%. The total water quality was improved by an average of 14%. The water was tested just after the excess discharge period, which took place in October and November. Surplus water was discharged from Aswan High Dam into the river in a process called "*Washing the Nile*". This helps decrease the concentration of pollutants like organic material, excessive salts and bacteria. The main industrial pollutants in the Nile are pesticides, organic material, heavy metals, ammonia, nitrate, and phosphate, but these pollutants are concentrated in limited areas where factories and industrial workshops discharge their liquid waste. Treated wastewater also finds its way into the Nile. The government is managing this arrival by deriving a large quantity of treated sewage water to tree plantations instead of diverting it into water channels. Over 4,620 ha of land were planted with trees in 24 areas across 16 provinces for this purpose and 2.4 billion cubic meters are being used for irrigation. Water quality awareness is still the new challenge for the Egyptian government, which is more important in solving environmental problems. This should begin with the people's recognition that a problem of water quality exists (***Chenini, 2010***).

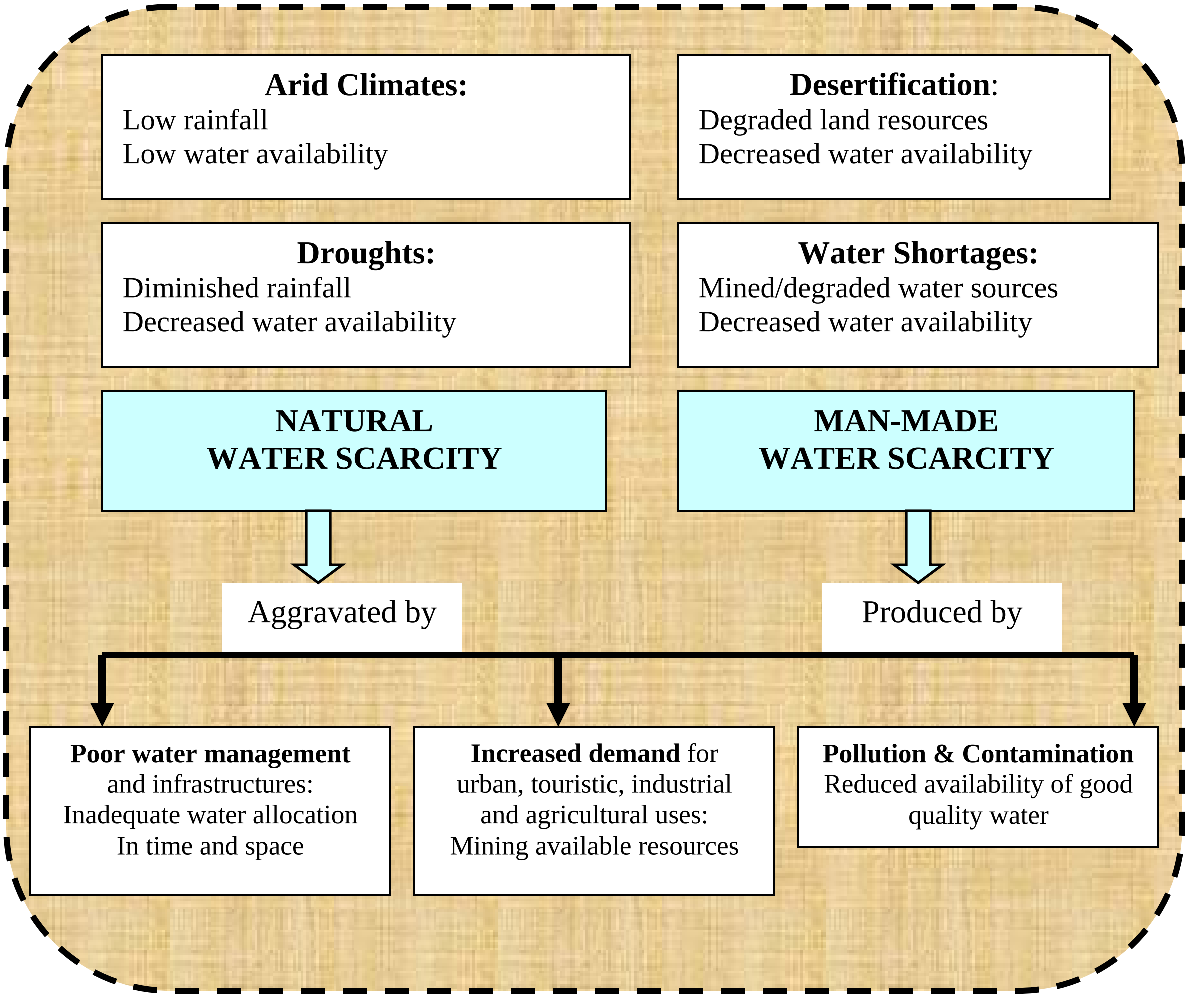


Figure 4.4: Natural and man-made water scarcity (adapted from ***Pereira et al. 2009***)

4.4 *Nile Basin climates*

The climate of the Nile Basin is characterized by a strong latitudinal wetness gradient. Whereas the areas north of 18° N remain dry most of the year, to the south there is a gradual increase of monsoon precipitation amounts. Rainfall regimes can be divided into nine types, among which summer peak regimes dominate. In the southern half of the basin, mesoscale circulation features and associated contrasts in local precipitation patterns develop as a result of a complex interplay involving topography, lakes and swamps. Precipitation changes and variability show up as three distinct modes of variability. The river Nile has the world's longest stretch under arid conditions: along 3,000 km of its course, rainfall does not exceed 150 mm annually. However, due to its great latitudinal and altitudinal extent, the Nile basin displays large variations in precipitation receipt. These contrasts, which clearly show up in the mean climate fields, also manifest in time as large year-to-year or longer-term fluctuations. Drying trends since the 1950s are found in central Sudan and to some extent the Ethiopian Highlands. The equatorial lakes region is characterized by occasional very wet years (e.g. 1961, 1997). The interannual variations are strongly, but indirectly influenced by El-Nino/Southern Oscillation. Sea surface temperature variations over other ocean basins, especially the Indian and South Atlantic Oceans, also play a significant role. Projections for the late twenty-first century show a 2–4°C temperature increase over the basin, depending on the scenario, but rainfall projections are more uncertain. Most models tend to predict a rainfall increase in the equatorial regions, but there is little consistency between models over the tropical regions (***Camberlin, 2009***).

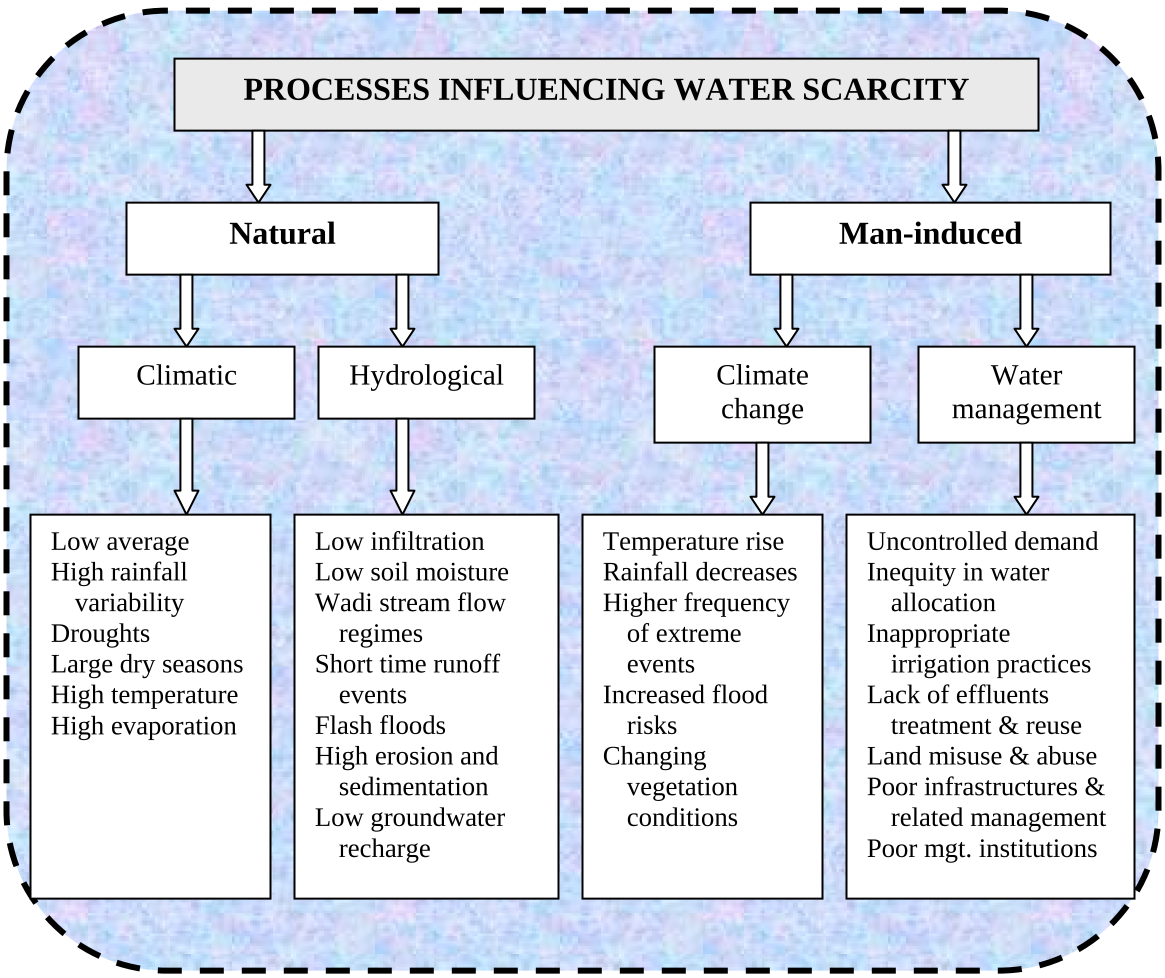


Fig. 4.5: Natural and man-induced processes favoring water scarcity (adapted from ***Pereira et al. 2009***)

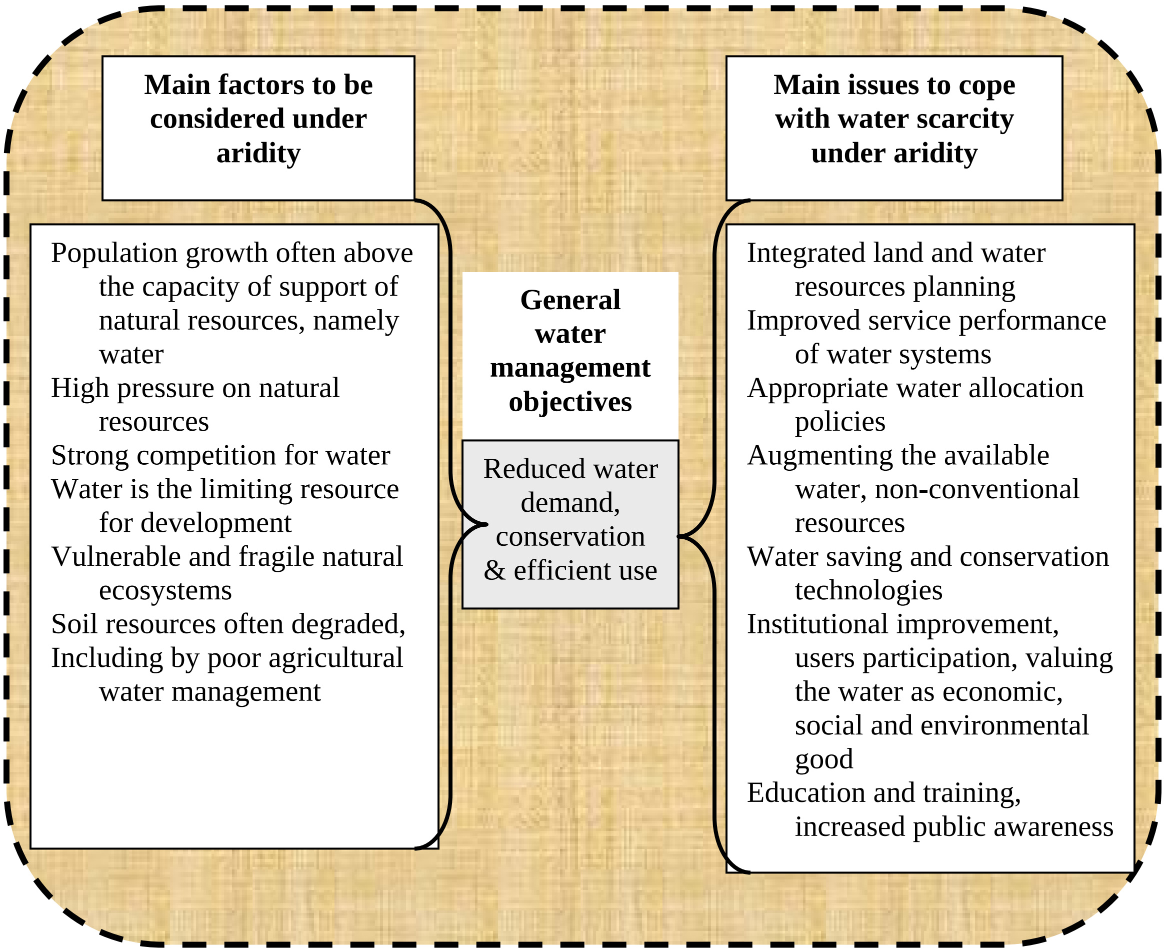


Figure 4.6: General framework for coping with water scarcity due to aridity: main factors, objectives and issues (adapted from ***Pereira et al. 2009***)

The Nile basin extends over 35 degrees of latitude, from the equatorial zone (4° S) to the northern subtropics (31° N). This results in highly contrasted climatic conditions, dominated by the Hadley circulation. The Hadley circulation is fuelled by a north–south energy gradient between a zone with excess energy (to the south of the basin, shifting to the central part with the northern summer heating) and a zone with a deficit (to the north of the basin). The excess energy originates from high solar radiation gains, low terrestrial radiation losses due to an extensive cloud cover, and a high atmospheric moisture content (latent heat). The deficit in the north, mainly the Sahara desert, is related to lesser solar radiation gains (in the northern winter), to high terrestrial radiation losses due to cloudless skies, and to a dry atmosphere (low latent heat content) (***Camberlin, 2009***).

The mean annual rainfall for the Nile basin is low (630 mm over the period 1961–1990), but it is spatially very contrasted. As much as 28% of the basin receives less than 100 mm annually, and part of it experiences hyper-arid conditions. However, a substantial area exhibits sub-humid conditions (34% between 700 and 1,300 mm), as displayed on the frequency distribution plot. Spatially, there is a very gradual decrease of rainfall amounts from south to south in the central part of the basin (about 100–140 mm per degree of latitude). North of about 18° N, from northern Sudan all across Egypt, rainfall is negligible (below 50 mm a year), except for a small increase along the Mediterranean coast (Alexandria 180 mm). Precipitation in excess of 1,000 mm is restricted to two areas: the equatorial region from south-western Sudan to most of the Lake Victoria basin, and the Ethiopian Highlands. Even in these two areas, precipitation amounts are contrasted, with maxima around 2,100–2,300 mm near Gore, south-western Ethiopia, 2,200 mm over the western part of Lake Victoria, 2,000 mm on the western slopes of Mt Elgon. Localized values over 2,500 mm are found on Mount Rwenzori (***Osmaston and Kaser, 2001***), and perhaps over 3,000 mm on the western slopes (***Leroux, 1983***). Parts of the Western Rift Valley (Lake Edward, Lake Albert), north-eastern Uganda, and areas to the west and south of Lake Victoria get less than 900 mm (***Camberlin, 2009***).

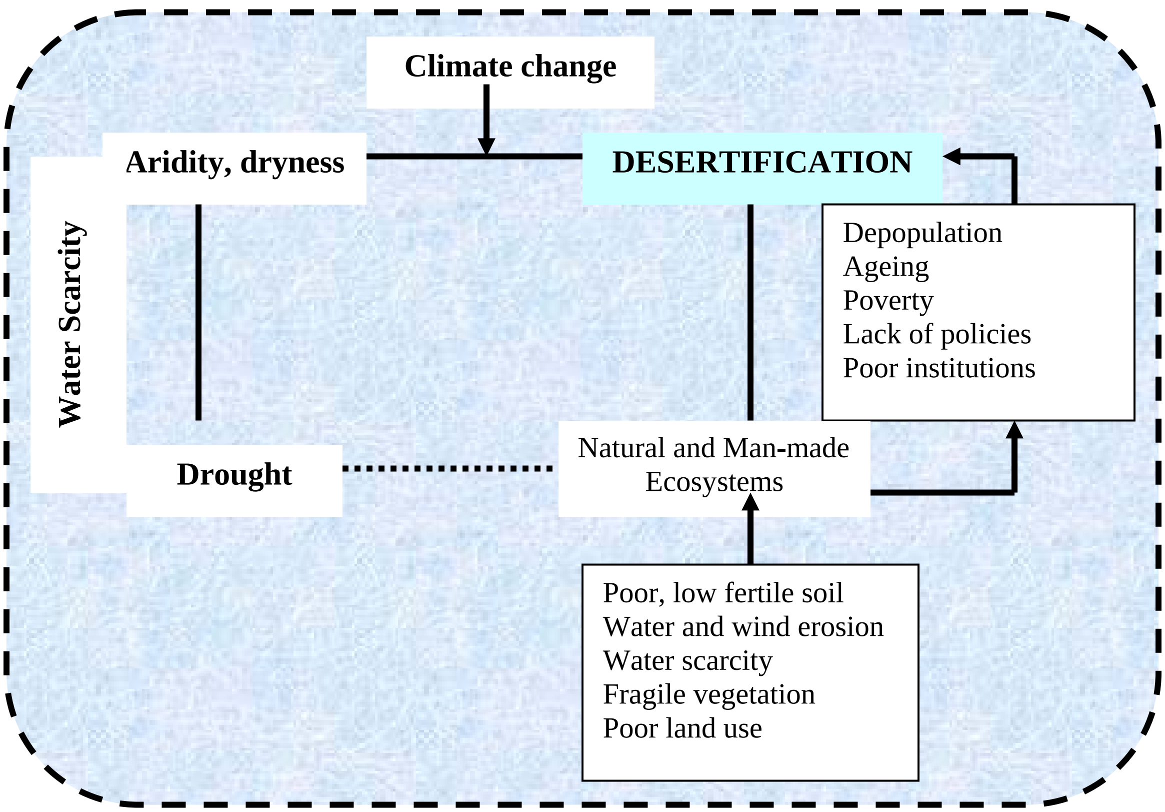


Figure 4.7: The circle of desertification processes with identification of the role of social, economic and institutional factors (adapted from ***Pereira et al. 2006***)

The drying trend which affected much of the Nile basin in the 1970s and 1980s, added to potential climate effects associated with increasing greenhouse gases concentrations in the global atmosphere, have prompted speculations about the future of the Nile basin climate. In the 1990s, twenty-first century projected climate changes for the Nile basin were focused upon in a series of studies dedicated to the assessment of water resources, based on a direct use of General Circulation Models (GCM) experiments. **Strzepek et al. (1996)** used three GCM (UKMO, GISS and GFDL) to evaluate future changes in the Nile water resources, under a doubled CO_2 hypothesis. A 15–17% increase in the basin-averaged rainfall was found for the first two models, and a 5% increase for the latter. Expected temperature rises ranged from 3.1°C to 4.7°C. A more detailed assessment, based on interpolated data from six GCMs, provided contrasted projections (***Yates and Strzepek, 1998***). While for the equatorial lake region almost all the models gave an increase in annual precipitation (0% to 26%), the projections for the Blue Nile catchment were between −9% and +55%. Temperature rises were more consistent among the models, as well as spatially. Inter-model differences in precipitation were also pointed out by ***Conway and Hulme* (1996)**, who used the GFDL and GISS models as well as a weighted ensemble mean from seven GCM experiments. Whereas all the experiments showed a temperature increase slightly under 1°C by 2025 with respect to 1961–1990, and fairly identical in the Blue Nile and Lake Victoria areas as well as in all the four trimesters considered, precipitation projections were more contrasted. Increases dominated over Lake Victoria, but large disparities in the Blue Nile region highlighted the difficulty for most models to simulate precipitation. More recently, **McHugh (2005)**, based on the four models out of 19 which best simulate East African rainfall, showed a projected rainfall increase in the equatorial regions, mainly due to a rise in DJF and MAM rainfall (***Camberlin, 2009***).

4.5 *The Nile: History of scientific research*

The Nile is a river rich in human history, which includes an ancient civilization and achievements of geographical exploration. Accounts of these are numerous, but there appears to be no general summary–history of scientific research on the river itself. The following outline has emphasis upon hydrobiology and its physical and chemical background. Many aspects of the Nile, including its scientific study, have been influenced by its great length combined with a south–north orientation. The latitudinal differentiation that results is unmatched in any other large tropical river. Past centres of scientific activity were widely separated; they operated under varied climatic conditions and sources of support. Longitudinal sampling and measurements also depended on feasibilities of transport and navigation (**Figure 4.8; *Talling, 2009***).

Figure 4.8: The Nile basin (www.wikipedia.con/10.1.2012)

The ancient Egyptian civilization left abundant pictorial records (as in tomb paintings) of river and swamp scenes and their larger biological components. Papyrus and lotus were extensively stylized and were symbols of Upper and Lower Egypt. Species of riverine birds can be recognized, as can distinctive Nilotic fishes such as the Nile perch, *Lates niloticus*. Hydrology began with maintained records of river level, of which examples after 600 A. D. have been re-analyzed in modern times (***Hassan, 1981***). But the sources of the river, and the origin of its annual flood, were unknown when the Greek traveller and historian Herodotus visited Egypt about 460 B. C. More than two thousand years later the Jesuit Father Lobo made the crucial connection (***Southwell, 1668***) between seasonal rains in Ethiopia and floodwater in Egypt – although possibly some inkling of this had not escaped inhabitants of the old intermediate centres of Meroë and Sennar. Travellers in the seventeenth to nineteenth centuries brought observations and samples that were recorded in scientific literature, mainly European. Plant and animal specimens were the foundation for later taxonomy, floristics and faunistics. Celebrated field collectors included the German botanist Schweinfurth and the zoologist Stuhlmann who first dipped a plankton net into Lake Victoria (***Stuhlmann, 1891***; ***Talling, 2009***).

Numerous studies of Nile science continued in Egypt, with centres at Alexandria, Cairo, Assiut and Aswan. They included hydrology and chemical characteristics (***Saad and Abbas, 1985***), plankton (***Habib et al. 1987***), and fisheries (***Latif, 1984***). Many are summarized in the book edited by ***Bishai et al. 2000***), that is centered upon the consequences of the Aswan High Dam and its impoundment, and also gives general accounts of the groups of plants and animals involved. In Sudan, work at Khartoum University continued on phytoplankton in the Blue and White Niles by Sinada and his students. By this time the former Hydrobiological Research Unit was assimilated within an Institute of Environmental Studies. The discovery and exploitation of oil reserves in the Sudd region involved impacts upon the river and issues of ecological conservation. For the Main Nile within Nubia, above Dongola, plans and associated surveys proceeded after 2000 with the creation of a new reservoir involving seasonal storage. Two biological invasions had influence in the headwaters at Lake Victoria. The Nile perch, *Lates niloticus*, had risen to abundance after its controversial introduction (***Jackson, 2000***) in the late 1950s, with adverse effects on the original fish fauna. The water hyacinth *Eichhornia crassipes*, entered the lake, probably from across the Zaire-Nile watershed, and during the 1990s was an extensive floating pest especially in northern waters. Both these situations led to numerous studies, as from the Fishery Research Institute (formerly EAFFRO) at Jinja (***Oguto-Ohwayo, 1988***) and other lakeside institutes at Kisumu (Kenya) and Mwanza (Tanzania). Besides such regional problems, there was renewed interest in the historical evolution of the Nile system as a whole (***Adamson et al. 1980***). The history of Nile science is probably unequalled amongst that of tropical and sub-tropical rivers for the length and subject-diversity of study. As in Africa more generally (***Talling, 2006***), successive phases have involved traveller-collectors and observers, locally based institutions, and international agencies (***Talling, 2009***).

4.6 *Effects of Climatic and Global Change on Water Scarcity*

Climate change projections for Mediterranean region derived from global climate model driven by socio-economic scenarios result in an increase of temperature (1.5 to 3.6°C in the 2050s) and precipitation decreases in most of the territory (about 10 to 20% decreases, depending on the season in the 2050s). Climate change projections also indicate an increased likelihood of droughts and variability of precipitation – in time, space, and intensity – that would directly influence water resources availability. The combination of long-term change (e.g., warmer average temperatures) and greater extremes (e.g., droughts) can have decisive impacts on water demand, with further impact on the ecosystems. Under all climate change scenarios in the Mediterranean region, available water resources decrease while irrigation demand increases (***Iglesias et al. 2007***).

Climate change drives much of the change evident in natural hydrological cycles, which is one of the greatest environmental, social and economic threats

facing the planet. Recent warming of the climate system, irrespective of the causes is indisputable, and is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level (**Figure 4.9**). The Intergovernmental Panel on Climate Change (***IPCC, 2007***) concludes that observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases. Other effects of regional climate changes on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers.
Anticipated impacts of climate change on fresh water resources and their management are reported to be as follows (***IPCC, 2007***):

- By mid-century, annual average river runoff and water availability are projected to increase by 10–40% at high latitudes and in some wet tropical areas, and decrease by 10–30% over some dry regions at mid-latitudes and in the dry tropics, some of which are presently water stressed areas. In some places and in particular seasons, changes differ from these annual figures.
- Drought-affected or water stressed areas will likely increase in extent.
- Heavy precipitation events are very likely to increase in frequency and intensity, and thus to augment flood risks.
- In the course of the century, water supplies stored in glaciers and snow cover are projected to decline, reducing water availability in regions supplied by meltwater from major mountain ranges, where more than one-sixth of the world population currently lives.

Impacts of climate change are of diverse nature (**Figure 4.10**). They refer to losses in biodiversity due to changes in environmental conditions affecting the ecosystems. The present boundaries of natural ecosystems may change due to modifications in climate regimes; actual crop patterns may have to be modified due to changes in environmental conditions influencing the crop cycles, development and production. Rainfed crops are therefore more vulnerable than irrigated ones due to changes in precipitation, infiltration, evapotranspiration and soil moisture regimes. Food security is therefore threatened in more vulnerable regions and countries of the world. Changes in rainfall regimes will induce changes in stream flow regimes and lower base flow is expected. Moreover, the water quality regimes will also change and contamination impacts may be larger, affecting public health. The latter may also be impacted due to increase of frequency and severity of heat waves and wildfires. Overall, the water availability is expected to decrease thus enhancing competition among users and making it more difficult to satisfy the increased urban water demand for residents and tourism. It is important to recognize climate change as a process driving exacerbated water scarcity and threatening development in developing countries. Unfortunately, many other processes and driving forces are contributing to degradation of Earth's environment and people's welfare, including devastating wars. Nowadays, it is possible to identify within regions several situations that are expected to arise due to climate change (***Pereira et al. 2009***).

Water scarce regions are highly vulnerable to climate change impacts. Coping with water scarcity involves therefore requires that such impacts be recognized and appropriate mitigation and adaptation measures be developed and implemented to effectively cope with it (**Figurer 4.11**). In general with the increase in temperature it is likely that there will be an increase of potential evapotranspiration and therefore a higher vegetation and crops demand for water as well as impacts due to heat waves.

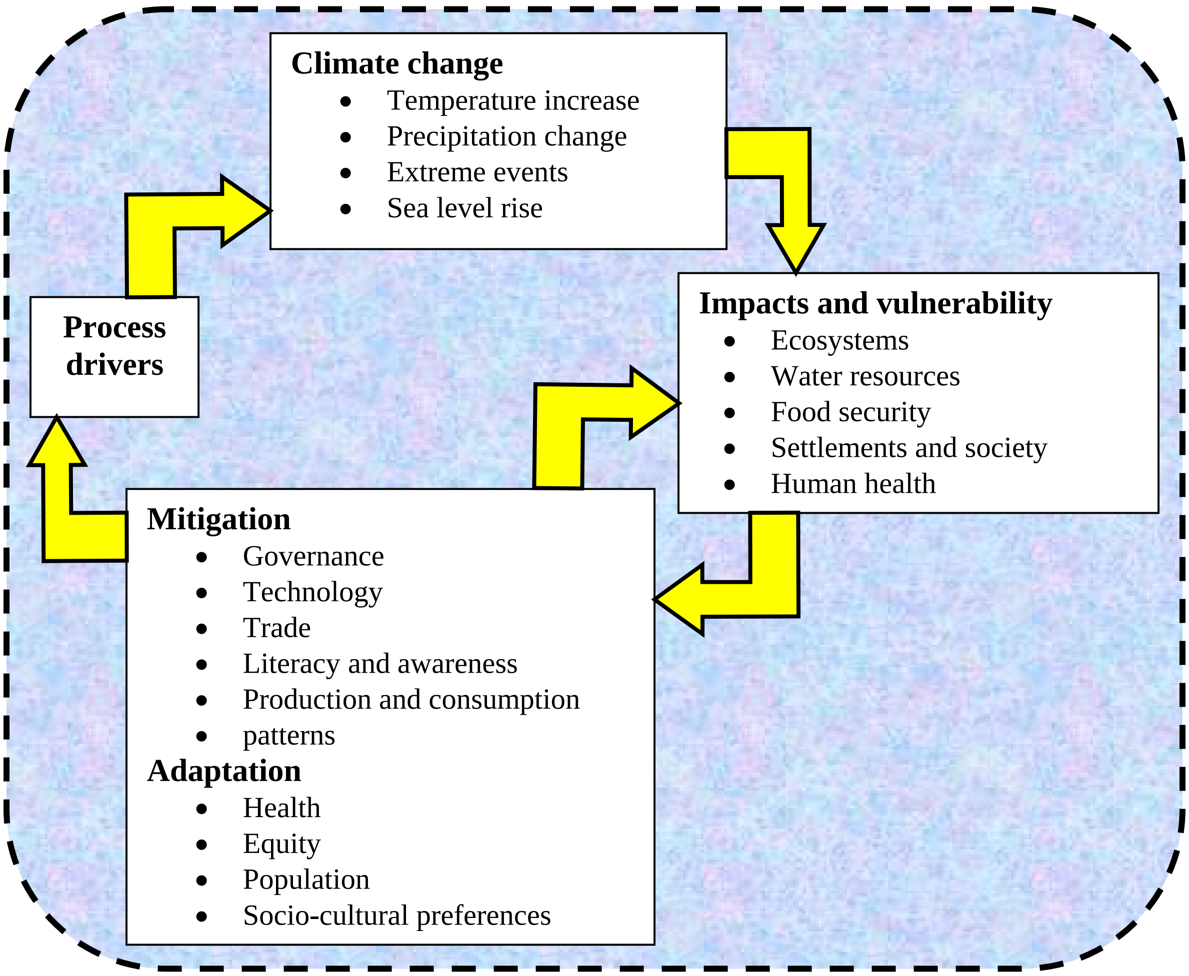


Figure 4.9: Climate change, impacts, and mitigation and adaptation responses (modified from ***IPCC, 2007***)

Figure 4.11 shows an attempt to consider some of the key ideas influence water resources development, and therefore also impact strategies for coping with water scarcity. As has been mentioned in previous chapters, water scarcity may be due to natural causes – aridity and droughts – or to man-made causes. Man-made scarcity is produced through a wide range of problems that may include: (1)

pollution or contamination by upstream users – urban, industrial, mining – causing degradation of that water before it can be accessed by downstream users, (2) poor water management such that there are strong inequities in allocations both in time and space between potential users, and (3) insufficient or inadequate infrastructure for water collection, storage, conveyance and distribution, especially during periods of stress, and when infrastructure maintenance is poor. Water scarcity problems are different among various groups of the population and users, e.g. rural *vs*. urban populations, environmental *vs.* human and economic uses, or domestic and industrial *vs.* irrigation uses. A key issue is controlling the demand for access to water, since the demand for water is everywhere growing very rapidly, including in water scarce areas (**Table 4.3**).

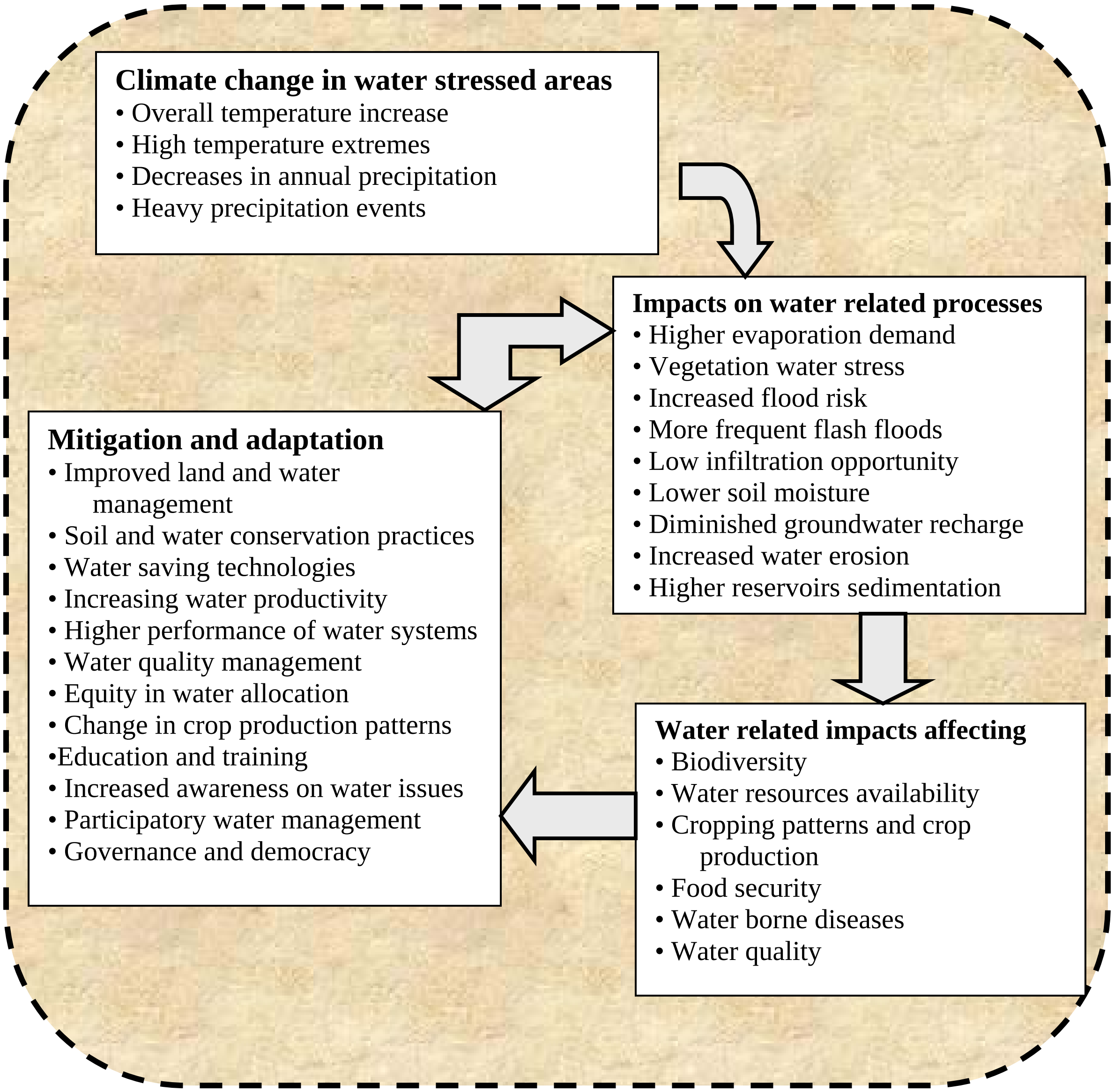


Figure 4.10: Climate change impacts on water scarcity and related mitigation and adaptation measures (adapted from ***Pereira et al. 2009***)

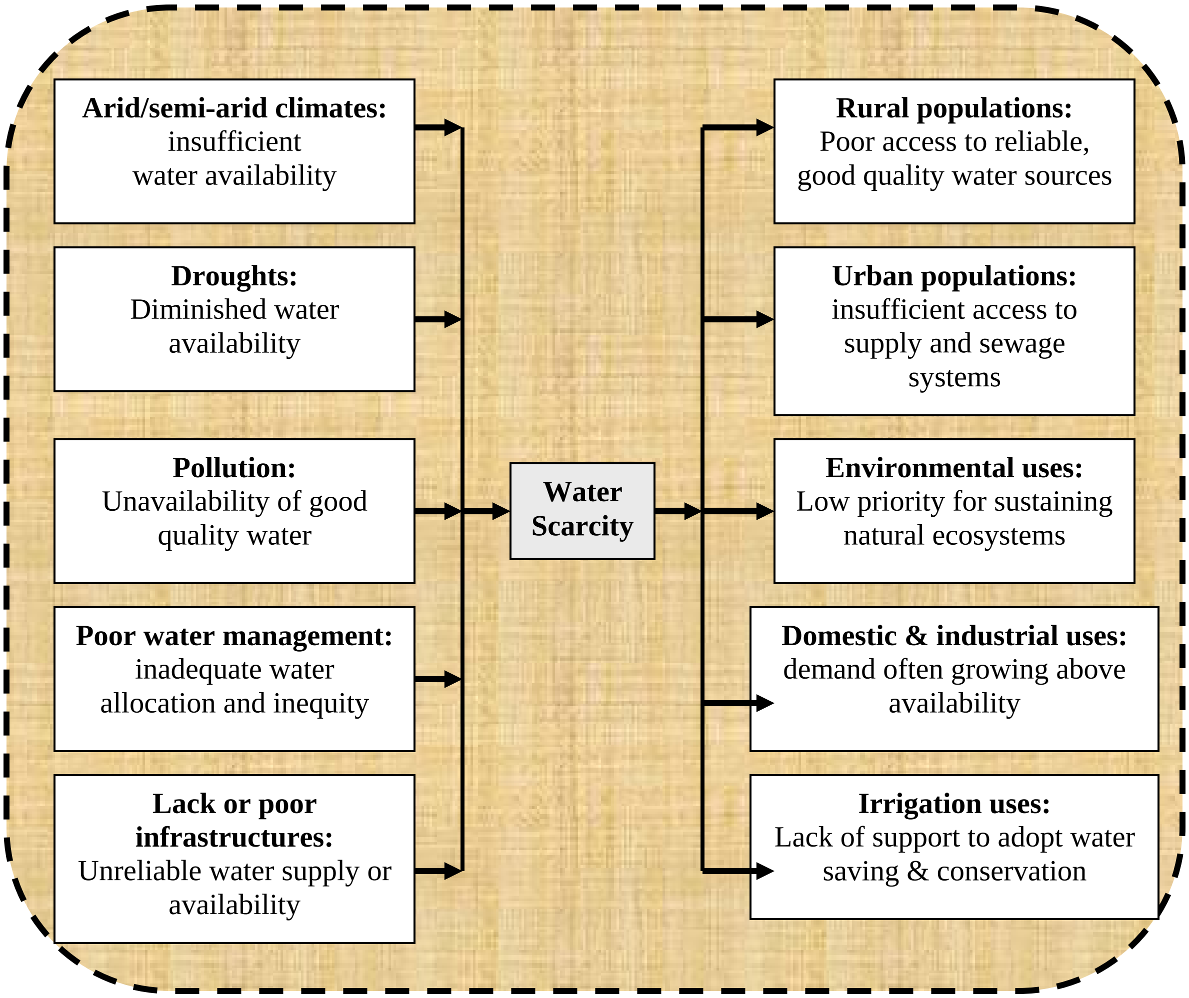


Figure 4.11: Framework for conceptual thinking on coping with water scarcity (adapted from ***Pereira et al. 2009***)

Global change is an expression of the human footprint on resources, energy and soil uses, directed to larger and less efficient agglomerations, higher use of resources, and a potential higher pressure towards natural ecosystems. As an expression of this global change, ecosystem and societal requirements compete for water resources, and this competition increases with increasing water scarcity. Aquatic ecosystems are impacted in a nonlinear way with increasing water withdrawal. The effects of drought and water scarcity on river ecosystems are evidenced by an extended duration of dry periods as well as by a growing proportion of watercourses being affected. Current estimates predict that on average, the global annual runoff is increasing (***Labat et al. 2004***). However, remarkable variations occur at the regional and local scales. While high-latitude catchments may experience an increase in runoff, tropical and mid-latitude watercourses are expected to experience a reduction in flow.

Table 4.3: Typology of climate change impacts on major agricultural systems (adapted from ***Connor et al. 2009***)

System	*Current status*	*Climate change drivers*	*Vulnerability*	*Adaptability*
Deltas				
Ganges-Brahmaputra	Densely populated. Shallow groundwater, extensively used. Flood adaptation possible; low productivity	Rising sea level. Storm surges, and Infrastructure damage. Higher frequency of cyclones (East and South-East Asia). Saline intrusion in groundwater and rivers. Increased flood frequency. Potential increase in groundwater recharge.	Very high (flood, cyclones)	Poor except salinity
Nile River	Highly dependent on runoff and Aswan Storage possibly sensitive to upstream development		High (population pressure)	Medium
Yellow River	Severe weather scarcity		High	Low
Red River	Currently adapted but expensive pumped irrigation and drainage		Medium	High, except salinity
Mekong River	Adapted groundwater use in delta; sensitive to upstream development		High	Medium
Semi-arid and arid tropics: limited snow melt and limited groundwater				
Monsoonal: Indian subcontinent	Low productivity. Overdeveloped basin (surface water and groundwater)	Increased rainfall. Increased rainfall variability. Increased drought and flooding. Higher temperature	High	Low (surface irrigation); medium (groundwater irrigation)
Non-monsoonal: sub-Saharan Africa	Poor soils. Flashy water systems. Over-allocation of water and population pressure in places. Widespread food insecurity	Increased rainfall variability. Increased frequency of droughts and flooding. Lower rainfall, higher temperature. Decreasing runoff.	Very high. Declining yields in rainfed systems. Increased volatility of production	Low
Non-monsoonal: Southern and	Western Australia Flashy water systems. Over-allocation of water. Competition from other sectors		High	Low
Mediterranean				
Southern Europe	Increasing pressure on water	Significantly lower rainfall and higher temperatures. Increased water stress. Decreased runoff. Loss of groundwater reserves.	Medium	Low
Northern Africa	High water scarcity		High	Low
West Asia	Heavy pressure on water		Low	Low

The predictions of the Intergovernmental Panel on Climate Change (***Milly et al. 2005; IPCC, 2007***) indicate that annual average river runoff might increase by 10–40% at higher latitudes, and may decrease by 10–30% in dry regions. An increase in flow has already been noticed for Scotland (***Werritty, 2002***). In Europe, the southern and south-eastern regions already suffer most from water stress and will see a further increase in the frequency and intensity of droughts (***EEA, 2008; Sabater and Tockner, 2010***).

Water withdrawal and scarcity are related to water flow regulation and dam construction. The regions suffering most from water scarcity are those which have a large number of big dams and reservoirs (***Tharme, 2003***). The global figures are also impressive. About 15% of the world's total runoff (40,000 km^3 yr^{-1}) is retained in 45,000 large dams higher than 15 m (***Nilsson et al. 2005***). From this retained volume, a further 10% is abstracted (***Voeroesmarty and Sahagian, 2000***). As a result of these manipulations and subsequent irrigation, up to 6% of the resources evaporate (***Dynesius and Nilsson, 1994***). A total of 52% of the surface area connected by large river systems (with a discharge of over 350 m^3 s^{-1}) is heavily modified, Europe containing the highest fraction of altered river segments. Arid and semi-arid regions are particularly water-thirsty, further increasing the pressure on water resources and causing extended dry river networks. However, this is already a global phenomenon. The Yellow River in China, for example, ceases to flow along extensive reaches (***Fu et al. 2004***). In 1997, during a particularly dry year, more than 700 km of river channel remained dry for 330 days. Similarly, sections of the Lower Colorado and Rio Grande Rivers in SWUSA remain dry at the surface for extended periods (***Molles et al. 1998***), thereby affecting the ecosystem viability (***Sabater and Tockner, 2010***).

A subsequent consequence of altered hydrological conditions is the export of solutes, as well as changes of the biogeochemical processes (**Tables 4.4, 4.5 and 4.6**) that derive from drought and rewetting. It has been observed that antecedent droughts in wetlands contribute to the oxidation of sulphides stored in the sediment to sulphates, which are mobilized after rewetting (***Sabater and Tockner, 2010***).

Finally, water scarcity refers to a situation where there is insufficient water to satisfy normal human water needs for food, feed, drinking and other uses, implying an excess of water demand over available supply. It is a relative concept, therefore, difficult to capture in single indices (***Falkenmark, 2007***). Water scarcity and an uneven distribution of freshwater resources are exacerbated by expected rapid demographic growth. **Voeroesmarty et al. (2000)** has compared possible global precipitation changes induced by climate change and water demands controlled by population growth. Their predictions indicate that the impact of increasing water demands derived from population growth is larger than the effects of climate change; the latter includes both an increase of aridity in some areas and an increase of rainfall in others. **Conway (2005)**, in a review of ten studies undertaken on Nile flow and climate models since 1981, similarly concluded that the climate-related impacts of variable Nile flow will be relatively minor in comparison with other human-induced changes, namely, population growth, land use choices, and development strategies (***Sowers et al. 2010***).

Table 4.4: Summary of effects caused by water scarcity (adapted from ***Sabater and Tockner, 2010***)

Water quality descriptor	***Effect of low flow***	***Effect on biota***	***Affected process***
Temperature	Lower oxygen content Higher metabolic rates Combined effects with toxicants and nutrients	Invertebrates Fish All groups All groups	Decrease in oxygen availability Higher primary production Higher respiration rates General effects on structure and metabolism
Conductivity	Enhanced water salinity	All groups	Physiological regulation Changes in community composition
Organic matter	Accumulation of organic matter	Bacteria Primary producers	Slowed down decomposition? High oxygen Consumption High mineralization
Sediments	Siltation	Primary producers Invertebrates Fish	Reduced production Changes in community composition Difficulties in gas diffusion
Nutrient	Higher concentration; eutrophication	Primary producers Potential bottom up-effects	Higher gross primary production Lower efficiency on materials processing
Pollutants	Increase of pollutant concentration and enhanced effects on the biota	All groups Complex food web effects	Diversity decrease? Effects on metabolism Effects on material processing

4.7 *Climate change and Nile water availability in Egypt*

Egypt is located between 22° to 32° North and 24° to 37° East. It is bordered on the west by Libya, on the north by the Mediterranean Sea, on the south by Sudan, and on the east by the Gaza Strip, and the Red Sea. Its coastline extends for more than 3,500 km along the Mediterranean Sea and the Red Sea coasts. The Nile delta coast, which constitutes about 300 km, hosts a number of highly populated cities such as Alexandria, Port-Said, Rosetta, and Damietta.

Egypt's climate is semi-desert, characterized by hot dry summers, moderate winters, and very little rainfall. The country has areas with strong wind, especially along the Red Sea and Mediterranean coasts. Sites with an annual average wind speed of 8.0 – 10.0 m sec^{-1} have been identified along the Red Sea coast and about 6.0 – 6.5 m sec^{-1} along the Mediterranean coast. Average precipitation in the Ethiopian highlands (where much of the water in the Nile originates) is highest in July, August, and September, at 5.4 mm day^{-1}, and almost negligible between January and March. Egypt is fairly unique in the distribution of its population, land-use and agriculture, and economic activity which makes it extremely vulnerable to any potential impacts on its water resources and coastal zone. Despite being a large rectangular shaped country with an area of about a million square kilometers, its lifelines are constrained along a narrow T-shaped strip of land (which constitutes less than 5% of its land area) along the Nile and the coast around the Nile delta. The Nile supplies 95% of the country's total water needs, including water intensive irrigated agriculture along its banks and the delta. Agriculture is quite critical to the national economy as it employs 30% of the work force and contributes 17% to the Gross National Product (GNP). Major urban centers, commerce, and industrial activity are also confined to the narrow corridor along the Nile and the coast around its delta. The rest of the country is desert and does not support much population or economic (***Agrawala et al. 2004***)

Table 4.7 ranks risks of climate change to particular sectors in Egypt under climate change, keeping in mind its geographical and contextual characteristics of population density, land-use and economic activity, which play a critical role in conditioning its vulnerability. The potential impacts of climate change on coastal resources are ranked as most serious. Sea levels are already rising in the Nile delta due to a combination of factors including coastal subduction and reduced sediment loads due to the construction of the High Aswan Dam upstream. Climate change induced sea-level rise only reinforces this trend. In addition to this high biophysical exposure to the risk of sea level rise, Egypt's social sensitivity to sea level rise is particularly high. As discussed earlier in this section much of Egypt's infrastructure and development is along the low coastal lands and the fertile Nile delta also constitutes the prime agricultural land in Egypt. The loss of this land due to coastal inundation or to saline intrusion will therefore have a direct impact on agriculture, which in turn is critical to Egypt's economy.

Egypt's Nile delta with its coastal front on the Mediterranean is considered vulnerable to the impacts of climate change. In addition to expected rise in sea-level, shoreline erosion, stresses on fisheries and saltwater intrusion in groundwater create major challenges. These factors also produce stressful effects on water and agricultural resources, tourism and human settlements. Fragile and unique ecosystems such as the mangrove stands in the Red Sea, which stabilize shorelines and provide a habitat for many species, may also be threatened. The northern Egyptian lakes, which constitute about 25% of the total Mediterranean wet lands and produce about 60% of the fish products, are also highly vulnerable to the impacts of climate change. Since the lakes are relatively shallow, climate change can lead to an increase in water temperature, which could result in changes in the lake ecosystems as well as changes in yield. So far, in-depth studies on potential impacts of climate change on lake ecosystems are not available (***Agrawala et al. 2004***).

Table 4.5: Summary on irrigation scheduling techniques, tools, applicability, and effectiveness to cope with water scarcity (adapted from ***Pereira et al. 2009***)

Techniques	Tools/procedures	Applicability	Effectiveness
Soil water indicators			
Soil appearance and feel	Hand probe, shovel	Field crops	Depending on farmers experience
Soil electrical resistance as depending on soil water content	Porous blocks, and electrode probes	Cash crops; calibration and advice are desirable	Depending upon selected irrigation thresholds
Soil water potential	Tensiometers, soil psychrometers, pressure transducers	Tree crops and horticultural crops. Calibration and advice to farmers are desirable	Very high when thresholds are well selected. Inappropriate for low soil water thresholds
Soil water content	Soil sampling, neutron probe, TDR and capacitative sensors	All crops. Require calibration and support by experts	Very high when thresholds are well selected
Soil water content and potential	Neutron probe or TDR and tensiometers	Research	Very high
Remotely sensed soil moisture	Thermal infrared scanner	Large areas	Limited
Crop indicators			
Appearance and feel	Observation of plant (leaf) signs of stress	Crops that give sign of stress prior to wilting	Depending on farmers experience
Leaf water content	Sampling	Mostly for research	Limited
Leaf water potential	Pressure chamber, psychrometers	Mostly for research	Very high
Stomatal resistance	Porometer	Mostly for research	High
Canopy temperature (and crop water stress index)	Infrared thermometers	Field crops in large fields. Needs expertise and calibration	Very high when thresholds are well selected
Changes in diameter of stems or fruits	Micrometric sensors	Tree crops. Needs expertise and calibration	Depending upon selected thresholds
Sap flow measurement	Electronic sensors	Mainly tree crops. Requires expertise and calibration	Very high when thresholds are well selected
Climatic indicators			
Pan evaporation (and rainfall)	Evaporation pans and evaporimeters	Generally included in regional irrigation scheduling programs	High but depends on the way information is provided to farmers
Crop evapotranspiration (and rainfall)	Weather stations and crop coefficients	Generally included in regional irrigation scheduling programs	High but depends the way information is provided to farmers
Remote sensing			
Remote sensing of crop evapotranspiration	Vegetation Index (NDVI) from several Wavelength including the thermal infrared	Regional irrigation programs with farmers advice in near real time	Now becoming operative for farmers advice. Needs spatially distributed water balance model to support information

Table 4.6: Generalized examples of impacts and adaptations by sector (adapted from ***Pittock, 2009***)

Sector	Potential impact	Potential adaptation	Comments
Hydrology and water resources	Increased floods and droughts, loss of snowpack and glaciers; regional and seasonal water deficits; saline intrusion in some island and coastal aquifers	Flood plain zoning, review levees and dam safety; management, pricing, conservation, recycling; desalinization plants	Major dams, water diversions, irrigation projects possible, but expensive and controversial with further climate changes creating design problems
Land-based ecosystems	Biodiversity loss in bounded areas including mountains; increased fire risk; weed invasion; Stalinization	Landscape management, ecocorridors; fire protection; weed control; management	Increased management of natural ecosystems, with increasing species and system losses
Aquatic ecosystems	Stalinization of coastal aquifers and wetlands; low river flows; eutrophication	Barriers to saltwater intrusion (where possible); increase environmental flows, reduce nutrients	Impacts will compound problems from increased population and water demand
Coastal ecosystems	Coral bleaching; more toxic algal blooms, acidification	Reduce other stresses, seed coral; reduce nutrient inflows	Population growth and pollution are other vital factors
Agriculture, grazing and forestry	Increased drought and fire risk; effects on global markets; spread of pests and diseases; increased soil erosion; initial benefit from increased CO_2 offset by climate change	Management and policy changes, fire prevention, seasonal forecasts; market planning, niche crops, carbon trading; exclusion spraying; land management; plant breeding, changed farm practices, change crop or industry	Sustainability in question in many regions
Horticulture	Reduced winter chill for fruiting, pests and diseases, drought	Change management, relocate, chemical sprays	Opportunities for tropical fruits at higher latitudes
Fisheries	Changes recruitment, nutrient supplies	Research, monitoring, management	Not well understood
Settlements and industry	Increased extreme event hazards, coastal erosion, flooding and retreat	Zoning, design standards, disaster planning, insurance, coastal defenses, retreat	Coastal settlements worst hit, coastal realignments much more than simple rise up existing contours
Electricity industry	Need increased peak capacity for air conditioning, drought threatens cooling water	Building design, shade, solar powered air conditioning, renewable power with storage	Efficiency also affected, trend to renewable creates opportunities, changing price structure
Tourism	Increased heat index; loss of some attractions e.g., snow resorts, coral reefs, coastal wetlands	Cool tropical resorts, expand cooler resorts; alternative industries or relocate people	Losses and gains
Insurance	Increased exposure to 'natural hazards'	Revised building codes, rate incentives, zoning, reduced cover	This is happening now; may deter unwise developments
Human health	Expansion of range of vector-borne diseases, water supply issues, injuries from extreme events	Quarantine, eradication, control, window screens, medication, repellents, improve medical services, evacuation, refuges	Wealthy countries can cope, others may suffer

Table 4.7: Ranking of key climate change impacts and vulnerabilities in Egypt (adapted from ***Agrawala et al. 2004***)

Resource/ risk ranking	*Certainty of impact*	*Timing of impact*	*Severity of impact*	*Importance of resource*
Coastal resources	High-medium	Medium-low	High	High
Water resources	Medium	Medium	High	High
Agriculture (indirect impacts - mediated by sea level rise and water resource)	High-medium	Medium-low	High-Medium	High-medium
Agriculture (direct impacts- temperature, rainfall)	Low	Medium-low	Low	High-medium
Energy resources	Medium-low	Medium-low	Medium-low	Medium-low

Egypt is almost wholly dependent upon water that originates from the upstream Nile basin countries; Uganda, Ethiopia, Tanzania, Kenya, Rwanda, Burundi, Congo, and Eritrea and Sudan. The Nile is comprised of tributaries draining the Ethiopian highlands which contribute around 70% of overall Nile flow, with 50% from the Blue Nile, and 10% from the Atbara and 10% from the Sobat rivers. Most of the remaining 30% of Nile flow originates from Lake Victoria with additional contributions and losses from lakes in Uganda and wetland systems in Southern Sudan, hereafter referred to as the White Nile system. Because of Egypt's almost complete reliance on the Nile for freshwater it is essential for any analysis of climate change and Egypt to consider the possibility of climatically-induced changes in Nile flows. To do this it is necessary to understand the generic linkages between water and climate change and the specific characteristics of the Nile basin which determine how climate interacts with other factors to produce Nile flows. The range of adaptation options to cope with potential water stress over the medium to long-term should theoretically encompass the set of global, regional, and basin level factors that drive water availability and/or use in Egypt, shown schematically here in **Figure 4.12** (***Agrawala et al. 2004***).

Egypt is one of the African countries that has proved vulnerable to water stress caused by climate change. The water used in 2000 was estimated at about 70 km^3 which is already far greater than the available resources. Both water supply and demand are expected to be affected by climate change and SLR. A combination of salt water intrusion due to SLR and increased soil salinity due to increased evaporation are expected to reduce the quality of shallow groundwater supplies in the coastal areas. Rainfall measurements in coastal areas are unpredictable and it is difficult to expect whether rainfall is increasing or decreasing. The demand for water in Egypt is dominated by three major user groups: agricultural irrigation, domestic use, and industry. The agricultural sector consumes about 85% of the annual total water resource. It is therefore likely that any effects of climate change on water supply and demand will be dwarfed by a much larger increase in demand due to population growth (***El Raey, 1999***).

One of the most outstanding impacts of SLR on the water resources is that it will increase the occurrence of saline intrusion with contamination of groundwater resources in the coastal zone. The eastern part of Lake Manzala appears to subside at a rate of 4.5 mm yr^{-1}, faster than any other region along the Nile delta coast. SLR is expected to cause a landward shift of the salt wedge and to increase the rate of saline seepage to the topsoil of the delta. This may have a serious impact on agriculture and drainage conditions, and potentially on available groundwater resources in the upper Nile delta. In addition, the salinity in Lake Manzala may increase because of the stronger influence of tidal flows penetrating the lake. Changes in the salinity conditions of the lake may affect its ecology and fisheries and the accelerated SLR will enhance the increase in salinity. As for the Nile Basin, it was found that there is no clear indication of how the Nile river flow will be affected by SLR, due to uncertainty in projected rainfall patterns in the basin and the influence of complex water management and water governance structures. Furthermore, it is important to mention that decrease of water resources might increase friction among countries sharing the same water resources (e.g. Nile and Euphrates), and might lead to political unrest (***El Sharkawy et al. 2009***).

4.8 *Climate change and its impacts on Nile flows*

A number of papers have looked at the implications of fluctuations in Nile flows for water resources in Egypt, particularly since a prolonged period of low flows during the 1970s and 1980s. **Abu-Zied and Biswas (1991)** and **Conway and Hulme (1993)** considered the implications of climate fluctuations for water management with emphasis on the Nile. They stressed the uncertainties involved in predicting future climate change and that existing planning processes and hydrologic methodologies need to be improved to deal with such challenges. They also emphasized the importance of fluctuations in river flow over the historical period for managing water resources. **Hulme (1990)** reviewed the factors affecting precipitation over the Nile basin at different temporal and spatial scales. He presented future changes in temperature and precipitation, based on the results of a number of global climate model (GCM) experiments for the Nile basin, with a discussion of their implications for Nile flows. **Conway and Hulme (1996)** used hydrologic models of the Blue Nile and Lake Victoria to assess the magnitude of potential impacts of future climate change on Nile flows. The impacts were largely dependent on the wide range of inter-model differences in future climate, particularly associated with the direction and magnitude of rainfall change. A Lake Victoria water balance model similar to one first developed by the UK Institute of Hydrology (***Piper et al. 1986***) was driven with three climate change scenarios from three GCMs and produced changes in Lake Victoria outflows ranging from -9.2% to +11.8%. Sensitivity analysis showed that a 10% increase in Lake Victoria rainfall caused a 31% increase in runoff and a 4% increase in evaporation caused an 11% decrease in runoff. By combining changes in Lake Victoria outflows with changes in runoff in the other Nile sub-basins **Conway and Hulme (1996)** obtained a range of –9% to +12% change in mean annual Nile flows for 2025 (***Agrawala et al. 2004***).

Strzepek and Yates (1996) used a spatially aggregated monthly water balance model to explore the sensitivity of Nile flows to climate change. Like **Conway and Hulme (1996)** they found that there was divergence between climate model results for the Nile basin; from a sample of four models two produced increases and two produced decreases in flows, with one producing a decrease of over 70% of annual flow. In a later study **Strzepek et al. (1998)** found that five out of six climate models with a doubling of CO_2 produced an increase in Nile flows at Aswan, with only one showing a small decrease (-15%). Strzepek and colleagues have produced two recent updated studies with greater emphasis on developing methodologies for designing what they term as 'not implausible' climate and economic scenarios and for assessing and evaluating adaptation strategies. **Strzepek et al. (2001)** use a purpose designed software system to produce a sample population of climate change scenarios for the basin that incorporate uncertainties due to differences between climate models, a range of climate sensitivity estimates, emission pathways for greenhouse gases and sulphate aerosols and the effects of sulphates aerosols. They selected nine representative scenarios from the full range which were translated into future Nile flow scenarios using a suite of water balance models. The results showed a propensity for lower Nile flows (in eight out of nine scenarios), in contrast to their earlier study, in which five out of six scenarios produced an increase in Nile flows (***Agrawala et al. 2004***).

The importance of maintaining a distinction between rainfed and irrigated virtual water as it relates to national water management and international trade policy cannot be over-stated (***Aldaya et al. 2008***). The first approximation of virtual water 'trade' provided in the following section is based on an assumed rainfed and irrigated 'virtual water content' of select crop and livestock products, as shown in **Table 4.8**. For the purpose of this study, the virtual water content of a crop is defined as the amount of water that has been consumed by the crop by the time it is harvested, expressed in terms of the volume of water by weight of yield produced. In dry climates such as Egypt or Northern Sudan, the soil water component used by a crop is close to zero; that is, the crop is grown with fresh water through irrigation. In more humid climates such as the Kenyan highlands, little or no irrigation is applied, and the irrigation water component for such a region is nil. Some of the crops grown in the Nile Basin and in the Nile Basin economies are produced through a combination of soil water and irrigation water (***Renault, 2002***). The rainfed and irrigated components of virtual water content of crops presented in **Table 4.9** is taken from the FAO Nile Basin Dataset (***FAO, 2006***).

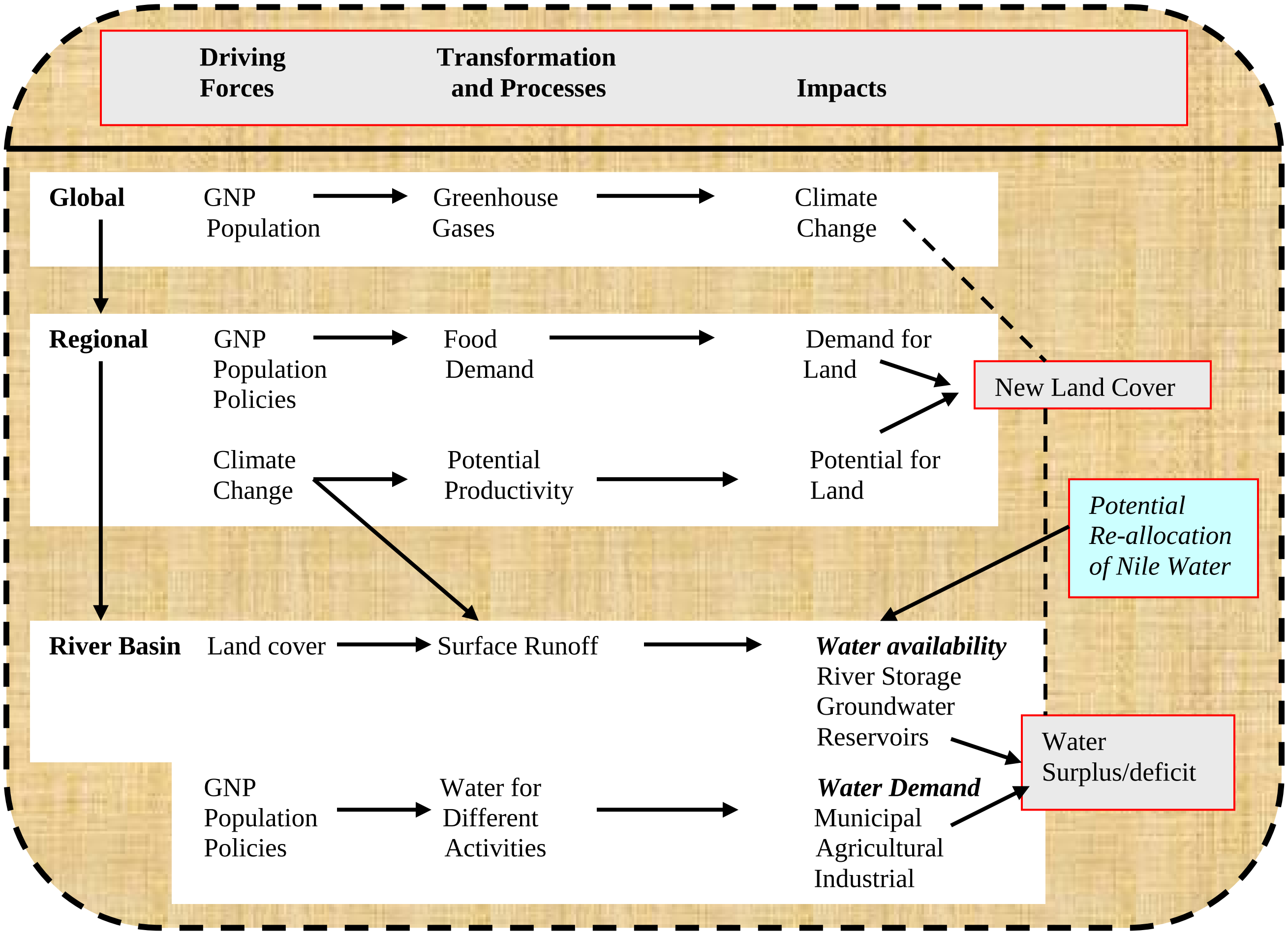


Figure 4.12: Multi-scale drivers affecting Nile water availability in Egypt (GNP, Gross National Product; adapted from ***Conway et al. 1996***)

4.9 *Climate variability and change in the Nile basin*

The source areas for the Nile are the humid highlands of East Africa and Ethiopia. Neither region experiences particularly high interannual rainfall variability, however, marked fluctuations in rainfall have occurred over decadal timescales with significant consequences for Nile flows. As it is possible to explain most of the variability in Nile flows by considering the Blue Nile (Ethiopian highlands) and Lake Victoria (East Africa, main component of the White Nile system) this section presents a hydroclimatic analysis of both regions and their integrated effects on the overall flows of the Nile (***Agrawala et al. 2004***).

Table 4.8: Virtual water content for select crops and livestock – rainfed component (m^3/metric tonne) (adapted from ***Zeitoun et al. 2010***)

Crops	**Egypt**	Sudan	Ethiopia	Eritrea	Uganda	Kenya	Tanzania	Rwanda	Burundi	DRC
Wheat			2021	2118	1319	1225	1907	3045	3462	1339
Rice					4178		4181	3176		6120
Maize		8406	1755	5321	2727	2318	2664	3197	2946	3691
Barley			2648	2883		1203	1506			
Lentils		7592	2444	3865	2422	3817	3711	2896	2746	2536
Potatoes			484		498	752	293	567	1112	509
Sugar					8292	1733		3251		2443
Beans		3603	2999	4180	5585	6523	5432	4470	2954	4077
Bananas			592		2539	2397	1169		1960	2854
Citrus			1497			1953				587
Soya			5730		17,792		59,354	40,351		17,816
Groundnut		24,400	7526	10,320	21,020	21,560	24,413	15,511	14,972	11,707
Coffee			9884		13,971	26,025	25,060	15,942	13,550	28,467
Tea		10,207	36,125		10,186	5401	7651	8250	12,425	14,748
Tobacco			7549		2904	1257	4680	2473	3903	6723
Cotton		13,011			13,676	10,229	12,870		6488	7735
Rubber										41,207
Chicken	8529	8529	3320	5443	5443	3942	8529	10,704	8789	8529
Pigs	6522	6522	5802	5011	5011	3616	6522	4991	5071	6522
Cattle	10,531	10,531	7972	9816	9816	6571	10,531	7745	7604	10,531
Sheep	4990	4990	3579	4196	4196	2991	3000	3440	3488	3000

Virtual water: the concept of 'virtual water' is established by **Tony Allan (1997)**, virtual water relates to the water used in the production of any commodity. The water consumed in the production of a laptop computer, for example, including all the freshwater used to produce the polymers and mine the silica. When any such commodity is traded, the production water 'embedded' in the product may also be considered to be 'traded'.

In the Blue Nile basin a slightly increasing trend occurred between 1905 and 1965 followed by a prolonged decline which bottomed out in 1984 and recovered during the 1990s with 1996 the wettest year since 1964 (33 years). In contrast, rainfall over Lake Victoria shows a moderate increasing trend up to 1960 followed by a prolonged increase in annual rainfall due to a combination of extremely wet years, e.g. 1961, 1963 and 1977 and small increases in other years. Annual rainfall over much of the Lake Victoria region increased from 1931-60 to 1961-90 by roughly 8% (***Conway, 2002***). Runoff in the Blue Nile basin amounts to 45.9 km^3 (equivalent to 1456 $m^3\ s^{-1}$), a depth of 261 mm (1961-1990), and a runoff coefficient of 18%. Between 1900 and 1997 annual river flow has ranged from 20.6 km^3 (1913) to 79.0 km^3 (1909), and the lowest decade-mean flow was 37.9 km^3 from 1978-87. A significant and sustained increase in Lake Victoria levels and outflows occurred in late 1961. Lake Victoria levels increased 2.25 m from 1961 to their peak in 1964 equivalent to an increase in storage volume of 151 km^3 and decreased steadily except for short-lived rises in 1978-79, 1990-91 and 1997-98 and they remain well above their pre-1961 levels. Lake Victoria outflows roughly doubled from 1931-60 to 1961-90. In contrast to an observed warming in parts of the basin during the 20th century (***Hulme et al. 2001***) there is no evidence of rainfall behavior that might be attributed to global warming. In terms of future climate change there is high confidence that temperatures will continue to rise, probably more rapidly than before, with implications for greater losses to evaporation and transpiration. For rainfall there is much less certainty, particularly because of the low convergence in climate model results for future rainfall conditions in the key headwater regions of the Nile. **Hulme et al. (2001)** found a large inter-model range in seasonal rainfall changes over Africa with a set of recent GCM experiments, including differences in the direction of rainfall change over Ethiopia. Inter-model disparities in future rainfall change are also presented in **IPCC (2001)**.

Table 4.9: Virtual water content for select crops – irrigated component (m^3/metric tonne) (adapted from ***Zeitoun et al. 2010***)

Crops	Egypt	Sudan	Ethiopia	Eritrea	Uganda	Kenya	Tanzania	Rwanda	Burundi	DRC
Wheat	1063	4941								
Rice	1249	10,684			2220	2655	2402	1879	2031	2289
Maize	865	7308	2314	3193			998		2880	
Barley	1221								2325	
Lentils	495	3824	1699	2046						
Potatoes	297	821		693						
Sugar	1517	2087	1261		3296	1353	1850		1603	
Beans	2169	2107	3124	4373						
Bananas	495	660	959							
Citrus	836	1397	1963			1539	2418			
Soya	18,371		7135							
Groundnut	7966	16,475								
Coffee						27,305				
Tea						6953				
Tobacco			5614							
Cotton	3053	7352	6880							

There remains low confidence in the direction and magnitude of future rainfall change in the basin, however, the observed regional warming and the high confidence (in IPCC terms) that this will continue at an increasing rate makes it prudent to review the possible effects of higher temperatures on surface water resources in the basin. That there are large expanses of open water (Lake Victoria alone is roughly 67 000 km^2) and wetlands, along with reservoirs (evaporation from the High Aswan Dam is over 10% of the Nile flow), long stretches of river channel in semi-arid to arid conditions, and extensive areas of irrigation in Sudan and Egypt suggests that surface water resources in the basin are likely to be quite sensitive to higher temperatures. Given no change in rainfall, higher temperatures will probably cause lower river flows, lake levels and reduced wetland extent. This section contains a discussion of the main losses to evaporation in the Nile system (based on figures in **Sutcliffe and Parks, 1999**) and a qualitative assessment of the effects of higher temperatures on these losses. There follows a short discussion of the role and importance of higher temperatures to water use in irrigation systems (***Agrawala et al. 2004***).

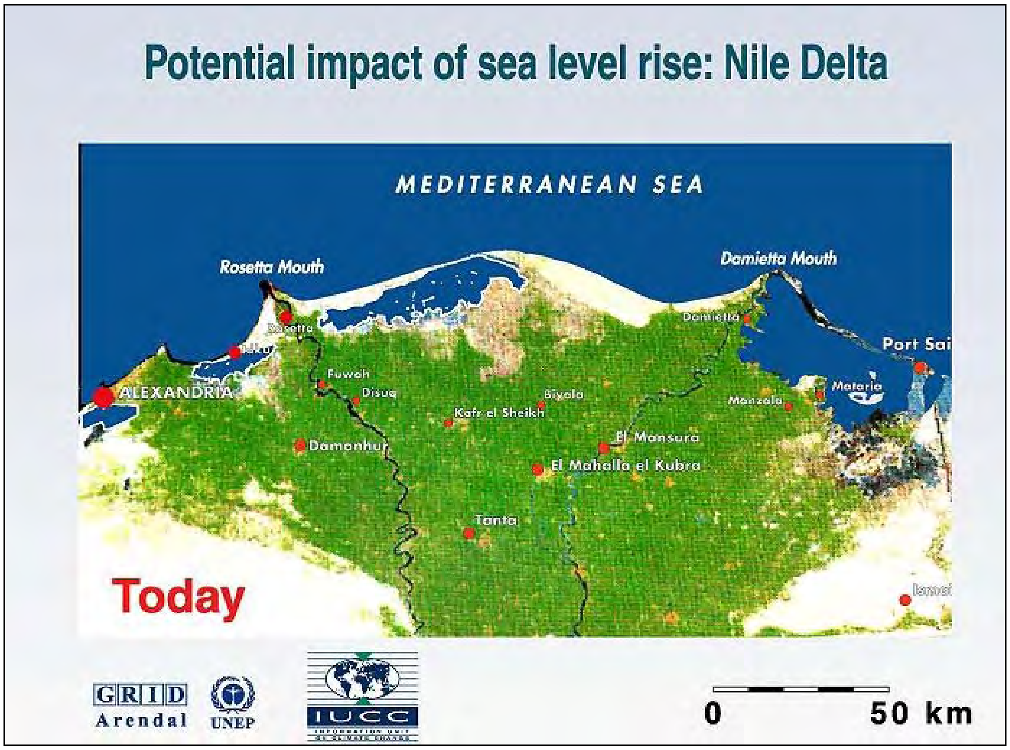
Losses to open water evaporation in Lake Victoria and the Ugandan Nile lakes, although lower than rainfall amounts are huge in volumetric terms. However, it is reasonable to speculate that some of this moisture may be recycled in the form of rainfall in the region. Evaporation rates begin to exceed rainfall when both the White and Blue Niles enter Sudan. Roughly half the inflows to the Sudd wetland system in Southern Sudan are lost to evaporation and transpiration (annual Penman evaporation is 2150 mm per year). Evaporation from the Blue Nile river between Roseires and Khartoum is roughly 2 km^3 (624 km length, 300 m width), Roseires and Sennar reservoirs have evaporation losses of roughly 0.5 km^3 each. On the White Nile, losses from north of the Sudd to just south of Khartoum (a distance of 840 km) are roughly 2 km^3 and the large surface area of the Jebel Aulia reservoir loses roughly 2.5 km^3. Channel losses from Khartoum to Dongola, close to the High Aswan Dam reservoir, are roughly 2.4 km^3 due to evaporation rates of 2700 mm over a channel length of 1500 km with average width of 600 m. Finally, in the High Aswan Dam reservoir and throughout Egypt, evaporation plays a critical role in water resources management. For the High Aswan Dam alone the estimated evaporation is around 10 km^3 (2700 mm evaporation) (***Agrawala et al. 2004***).

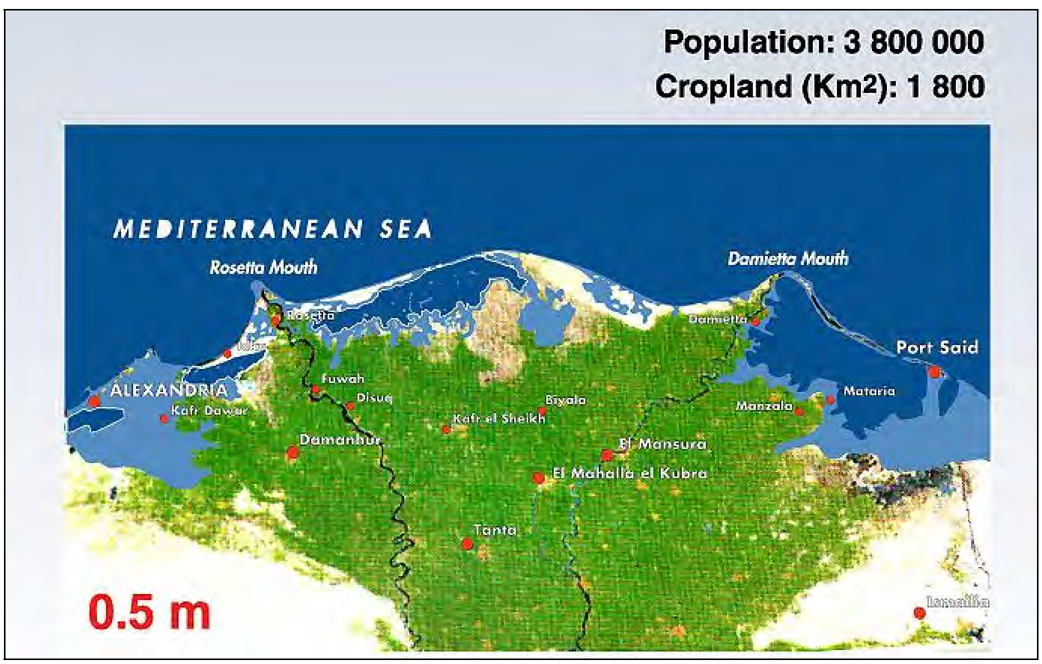
4.10 *The Impacts of Sea Level Rise on Egypt*

Vulnerability to climate change is considered to be high in developing countries due to social, economic, and environmental conditions that amplify susceptibility to negative impacts and contribute to low capacity to cope with and adapt to climate hazards. Moreover, projected impacts of climate change generally are more adverse for lower latitudes, where most developing countries are located, than for higher latitudes. Because of the high level of vulnerability, there is an urgent need in the developing world to understand the threats from climate change, formulate policies that will lessen the risks and to take action. The danger is greatest, where natural systems are severely degraded and human systems are failing and therefore incapable of effective response, specifically in deprived nations. Moreover, land degradation and desertification may also be exacerbated in these areas, posing additional threats to human well-being and development, added by intensified human pressures on lands and poor management. The livelihoods and food security of the rural poor are threatened by climate change with all its impacts, and the vulnerability to adverse health impacts is greater where health care systems are weak and programs for disease surveillance and prevention are lacking. In addition to multiple factors converging to make the people inhabiting coastal zones and small islands highly endangered from the causes of sea level rise (SLR). Egypt’s coastal zone of the Nile delta has been defined as a vulnerable zone as a consequence of SLR combined with geological and human factors (***El-Sharkawy et al. 2009***)

It is well documented that sea level changes are caused by several natural phenomenon; the three primary contributing ones are: ocean thermal expansion, glacial melt from Greenland and Antarctica -in addition to a smaller contribution from other ice sheets- and change in terrestrial storage. Among those, ocean thermal expansion has been expected to be the dominating factor behind the rise in sea level. However, new data on rates of deglaciation in Greenland and Antarctica suggest greater significance for glacial melt, and a possible revision of the upperbound estimate for SLR in this century. It is predicted that, with global warming, global average sea levels may rise by between 7 and 36 cm by the 2050s, by between 9 and 69 cm by the 2080s and 30–80 cm by 2100. The majority of this change will occur due to the expansion of the warmer ocean water. Since the Greenland and Antarctic ice sheets contain enough water to raise the sea level by almost 70 m, people will be directly affected by rising sea levels in several ways. As seas rise many areas of the coasts will be submerged, with increasingly severe and frequent storms and wave damage, shoreline retreat will be accelerated. In addition to expected disastrous flooding events caused by severe climate events such as heavy flooding, high tides, windstorms in combination with higher seas (***Dasgupta, et al. 2007***). The impacts of SLR will not be globally uniform, because of local variations in vertical crustal movements, topography, wave climatology, long shore currents, and storm frequencies. Low gradient coastal landforms most susceptible to inundation include deltas, estuaries, beaches and barrier islands, and coral reefs. Regions at risk include the Low Countries of Europe, eastern England, the Nile delta in Egypt, the Ganges–Brahmaputra, Irrawaddy, and Chao Phraya deltas of south-eastern Asia, eastern Sumatra, and Borneo. In the United States, the mid-Atlantic coastal plain, the Florida Everglades, and the Mississippi delta will be particularly vulnerable (***Vivian, 2005***)

The Nile Delta is one of the oldest intensely cultivated areas on earth. It is very heavily populated, with population densities up to 1600 inhabitants per square kilometer. The low lying, fertile floodplains are surrounded by deserts. Only 2.5% of Egypt's land area, the Nile delta and the Nile valley, is suitable for intensive agriculture. Most of a 50 km wide land strip along the coast is less than 2 m above sea-level and is protected from flooding by a 1 to 10 km wide coastal sand belt only, shaped by discharge of the Rosetta and Damietta branches of the Nile. Erosion of the protective sand belt is a serious problem and has accelerated since the construction of the Aswan dam (**Figure 4.13**). Rising sea level would destroy weak parts of the sand belt, which is essential for the protection of lagoons and the low-lying reclaimed lands. The impacts would be very serious: One third of Egypt's fish catches are made in the lagoons. Sea level rise would change the water quality and affect most fresh water fish. Valuable agricultural land would be inundated. Vital, low-lying installations in Alexandria and Port Said would be threatened. Recreational tourism beach facilities would be endangered and essential groundwater would be salinated. Dykes and protective measurements would probably prevent the worst flooding up to a 50 cm sea level rise. However, it would cause serious groundwater salination and the impact of increasing wave action would be serious.





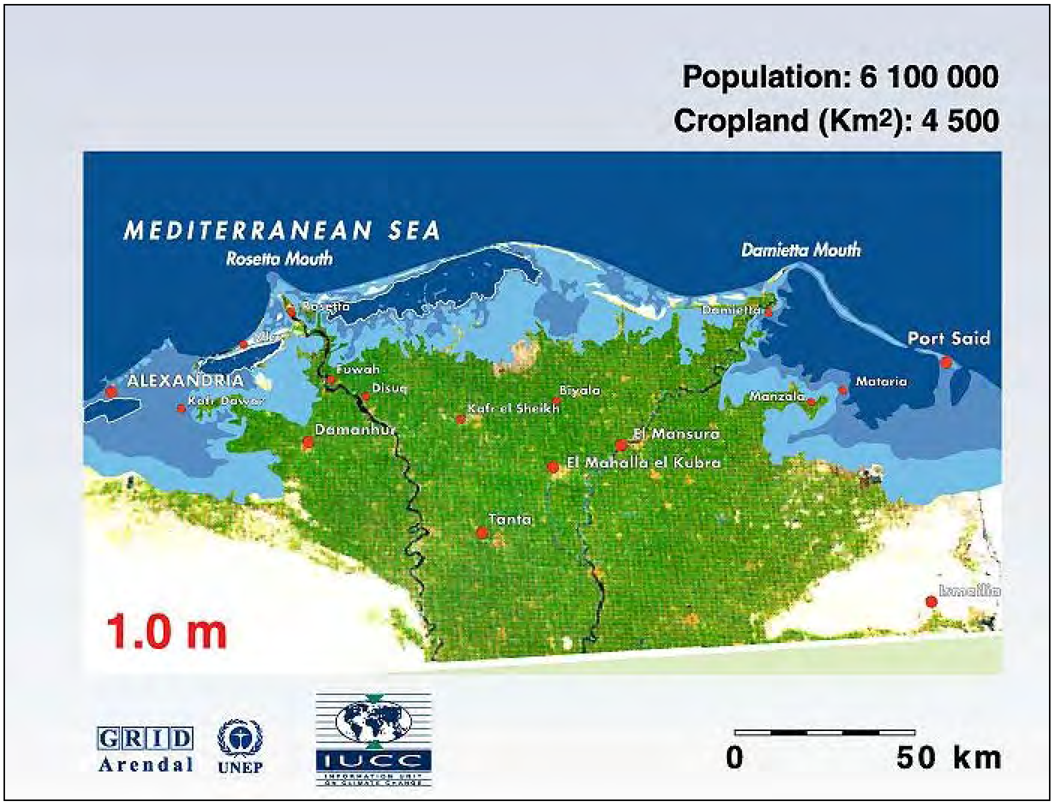


Figure 4.13: Nile Delta: Potential Impact of Sea Level Rise **(*Simonett, 2002*)**. In *UNEP/GRID-Arendal Maps and Graphics Library*. Retrieved 15:46, January 13, 2012 from http://maps.grida.no/go/graphic/nile_delta_potential_impact_of_sea_level_rise.

The Nile Delta is 200 km long and 255 km wide, within a coastline of over 1000 km on the Mediterranean Sea (**Figure 4.14**). The low sandy coast of the Nile Delta stretches with an arc between Ras Abu Quir to the west and the Bay of Tinah, to the east. Two branches of the Nile have formed the promontories at Rosetta and Damietta. Egypt's second largest city, Alexandria is located on the northwestern part of the coastal delta zone, with a population of 3.3 million in 1996, and more than 4.1 million in 2006 (***CAPMAS, 2006*** census). Alexandria is the main harbor of Egypt and hosts around 40 per cent of the country's industrial capacity, in addition to being an important summer resort and trading centre. Other large cities in the northern, low-lying delta zone include the rapidly growing city of Damietta and the historic city of Rosetta and Port Said City to the eastern side of the delta. The Nile delta region is fairly unique in the distribution of its population, topography, land-use, agricultural productivity and economic activities, which makes it extremely vulnerable to any potential impacts on its water resources and coastal zone (***El Raey, 2011***).

The River Nile supplies 95 per cent of the country's total water needs, including water intensive irrigated agricultural land along its banks and the delta. Agriculture is quite critical to the national economy as it employs 30 percent of the work force and contributes 17 per cent to the GNP (***IDSC, 2009***). Major urban centres, commerce, and industrial activities are also confined to the narrow corridor along the Nile and the coast around its delta. The rest of the country (about 95 percent) is desert and does not support much population or economic activity. The Nile Delta region lies within the temperature zone, which is a part of the great desert belt. The average temperatures in January and July in Cairo are 12 ºC and 31 ºC, respectively. Minimum and maximum temperatures in Cairo are 3 ºC and 48 ºC, respectively. Rainfall over the Nile Delta is rare and occurs in winter. Maximum average rainfall along the Mediterranean Sea shore, where most of the rain occurs, is about 180 mm. This amount decreases very The Nile delta region is the most fertile land of Egypt which depends mainly on water that reaches the region through the River Nile with resources on the Ethiopian hills and Lake Victoria some several thousand kilometres to the south. The Nile delta coast stretches about 300 km and hosts a number of highly populated deltaic cities such as Alexandria, Port-Said, Rosetta, and Damietta. These cities are also critical centres of industrial and economic activity. In addition, the Nile delta coastal zone includes a large portion of the most fertile low land of Egypt. The topography is generally sloping from the apex at Cairo to the Mediterranean coast at a rate of about 1 m/km with varying sand dunes, ridges and low elevation areas near the coast. The coastal zone of Egypt hosts five northern lakes which constitute about 25 percent of the wetland of the Mediterranean and are considered main sanctuaries for birds and fish resources (***El Raey, 2011***).

There are conflicting projections of the future availability of the water of the Nile as a result of climate change. **Yates and Strzepek (1998)**, using a monthly water balance model, reported that five of six *global circulation models* (GCMs) showed for doubled CO_2 levels increased flows at Aswan, with increases of as much as 137 % (UKMO). Only one GCM (GFDLT) showed a decline in annual discharge at Aswan (-15 %). The variations of the results indicate that more robust studies are needed to provide a more solid base for the design of public policy. However, the more plausible projections seem to point to a reduced availability of Nile water for Egypt in the future. In addition, **El Shamy et al. (2009)** confirmed this strong uncertainty using 17 IPCC models. This global sea-level rise combined with local land subsidence in many coastal areas, are expected to cause serious damage to many coastal ecosystems especially those of the low land deltaic coasts such as that of the Nile Delta in Egypt (***El Raey, 2011***).

Impacts of Sea-Level Rise on the Nile Delta

The impact of SLR on the Nile Delta can be divided into direct impacts of inundation and salt water intrusion and indirect impacts of loss of productivity, excessive soil salinity, health impacts and socio-economic implications.

(a) *Direct Impacts*

I. *Direct Impacts on Low Elevation Land in Cities*

The **IPCC's (1995)** *second assessment report* (SAR) has adopted a seven step common methodology for estimating vulnerabilities to sea-level rise which could be summarized as:

1. Choose a case study area and specify climate change boundary conditions;
2. Characterize a case study area (physical, socio-economic);
3. Identify key vulnerabilities (tourism, oil sector development, etc.);
4. Assess physical changes and natural system responses;
5. Formulate response strategies;
6. Assess vulnerability and interpret results;
7. Identify needs and actions.

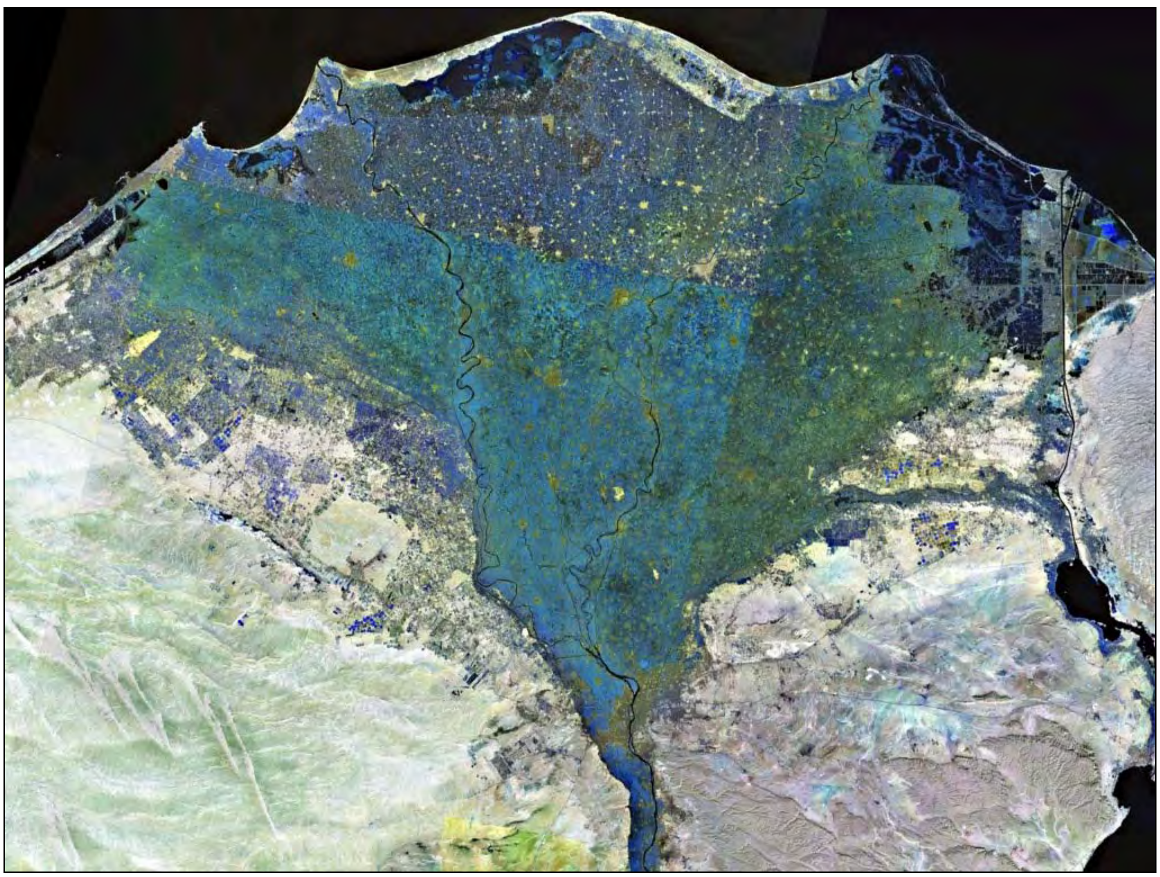


Figure 4.14: Satellite Image of Nile Delta. **Source:** Landsat 7 false color image of the Nile Delta; this image by NASA is in the public domain; at: www.answers.com/ 13.1.2012.

Climate change and seawater rise will affect the groundwater quality in the Nile Delta aquifer in two ways. First, low lands along the shoreline will be submerged with seawater and the aquifer below these lands will be destroyed. Second, additional pressure heads will be imposed at the seaside causing more intrusion. A dynamic monitoring network for piezometric head and water salinity is needed for better assessment and mitigation of seawater intrusion in the Nile Delta aquifer. A monitoring system must be established to collect data on rates of soil and groundwater salinization (***El Raey, 2011***).

II. ***Direct Impacts of Salt Water Intrusion***

The Nile Delta aquifer system is a complex groundwater system. It is a leaky one, with an upper semi-permeable boundary and lower impermeable boundary. The aquifer is recharged by the infiltration from the irrigation net work, excess of irrigation water and little precipitation through the upper clay layer. It may also be recharged by any possible flow coming from the Upper Egypt aquifer. The increase in demand in the Delta area was covered by intensive pumping of fresh groundwater, causing subsequent lowering of the piezometric head and upsetting the dynamic balance between the freshwater body and saline water body in the aquifer. Like any coastal aquifer, an extensive saltwater flux has intruded the Nile Delta aquifer forming the major constraint against aquifer exploitation. Climate change and seawater rise will affect the groundwater quality in the Nile Delta aquifer in two ways. ***First***, low lands along the shoreline will be submerged with seawater and the aquifer below these lands will be destroyed. ***Second***, additional pressure heads will be imposed at the seaside causing more intrusion. A dynamic monitoring network for piezometric head and water salinity is needed for better assessment and mitigation of seawater intrusion in the Nile Delta aquifer. A monitoring system must be established to collect data on rates of soil and groundwater salinization (***El Raey, 2011***).

III. ***Direct Impacts of Extreme Events***

The region is well known to be exposed to a number of extreme events of sand storms (e.g. Saharan dust and Khamasin which covers the whole region) and marine storms (e.g. Nawwat which hit mainly the coastal areas), as well as a number of heat waves. These extreme events cause large damage to agricultural productivity, materials and health. Its impact may even cross the Mediterranean and cause damage on the European side. These extreme events are expected to increase in intensity and frequency due to climate changes (e.g. ***IPCC, 2007***). It is impossible to exclude the impacts of these storms on sea-level and circulation pattern in the coastal environment. Again a detailed assessment of the impacts of extreme events is still to be carried out. It should be noted here that a lot of data on extreme events is becoming available for downloading from satellites (***El Raey, 2011***).

(b) ***Indirect Impacts***

Indirect impacts of sea-level rise on the Nile delta region include socio-economic and health impacts due to increased salinity and loss of productivity of the land and consequent migration of population to other areas looking for jobs. Considering scenarios for sea-level rise until 2100, it is estimated that about 6 million people will abandon the saline land in the northern delta and move to southern areas looking for jobs (e.g. ***Dasgupta et al. 2007***).

Vulnerability to climate change and adaptation options for coastal resources

Vulnerability can be defined as "*the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity*" (***Watson, 2001***). Vulnerability to climate change is considered to be high in developing countries due to social, economic, and environmental conditions that amplify susceptibility to negative impacts and contribute to low capacity to cope with and adapt to climate hazards. Moreover, projected impacts of climate change generally are more adverse for lower latitudes, where most developing countries are located, than for higher latitudes. Because of the high level of vulnerability, there is an urgent need in the developing world to understand the threats from climate change, formulate policies that will lessen the risks and to take action (***El Sharkawy et al. 2009***).

Egypt's coastal zone of the Nile delta has been defined as a vulnerable zone as a consequence of SLR combined with geological and human factors. The danger is greatest, where natural systems are severely degraded and human systems are failing and therefore incapable of effective response, specifically in deprived nations. Moreover, land degradation and desertification may also be exacerbated in these areas, posing additional threats to human well-being and development, added by intensified human pressures on lands and poor management. The livelihoods and food security of the rural poor are threatened by climate change with all its impacts, and the vulnerability to adverse health impacts is greater where health care systems are weak and programs for disease surveillance and prevention are lacking. In addition to multiple factors converging to make the people inhabiting coastal zones and small islands highly endangered from the causes of SLR (***Leary et al. 2007***).

A number of important economic and commercial centres in Egypt will be exposed to the adverse effects of climate change. Especially the coastal cities of the Nile Delta will be most affected. It is urgent that strategic adaptation policies and plans are put in place and strong institutions and systems of supervision are established to enforce environmental laws. Several criteria are important for the assessment of various options for adaptation in coastal zones, including: net benefits, environmental impacts, robustness and flexibility, chance of success, feasibility and fairness. Using this experience the following generic options have been identified as the most promising adaptation policies and measures for the protection of the coastal zones in Egypt. Adaptation starts with identifying and assessing vulnerabilities of various sectors to potential impacts of climate change. It then involves determining and assessing available options to deal with the effects of expected climate change through a change in public policies and/or the erection of protective structures such as dams or the like (***El Raey et al. 1999***).

In his chapter "*Mapping Areas Affected by Sea-Level Rise due to Climate Change in the Nile Delta until 2100*" which included in the splendid book "*Coping with Global Environmental Change, Disasters and Security*", **El Raey (2011)** reviewed about the effect of climate change on sea-level rise in the Nile Delta until 2100. For the Nile delta region, **El Raey (2011)** mentioned that the following adaptation measures should be adopted and strictly enforced:

(1)	A National Institute for Climate Change should be established to build capacity and train human resources, to design the required institutional systems, integrate and coordinate activities among the various sectors. This Institute would focus on the study of possible adaptation policies while also spreading awareness of climate change effects and publicizing success stories on the different sectors.
(2)	Establishing an institutional capability for coastal monitoring, assessment and follow-up of plans.
(3)	Activation of the national committee on *Integrated Coastal Zone Management* (ICZM), building of geographic data bases, developing policies and programmes.
(4)	Upgrading resilience of the community through upgrading of infrastructure, building capacities and upgrading awareness.
(5)	Adopting of an *Integrated Coastal Zone Management* (ICZM) for coastal development and enforcing of *environmental impact assessment* (EIA) that takes climate change into account.
(6)	Use of wind and solar energy for water desalinization must be promoted and adequate financing for scientific research in these areas must be provided.
(7)	Development of local human resource skills in the field of mathematical *Regional Circulation Models* (RCMs) to allow future projections with the high degree of accuracy that is required for policy formulation.
(8)	Studies should be undertaken to determine possible adaptation options and criteria for the selection of water, agriculture and coastal sectors, which would make use of simple and low cost technologies.
(9)	Environmental laws should be firmly enforced and environmental assessments of projects must be mandatory. National projects should take expected climate change effects into consideration.
(10)	A comprehensive institutional setup for the protection of the coastal areas must be established with the aim of coordinating the efforts of the research community and the implementation agencies.
(11)	Nongovernmental organizations should be encouraged to upgrade the awareness among decision-makers and the public on the dangers posed by climate change and of the necessity to reduce over -consumption.

According to results of **El Shennawy (2009)**, these general processes and policies are proposed:

- ❖ Sand dunes systems should be treated as the first defensive line for the Nile Delta.
- ❖ Utmost consideration should be paid to coastal lakes as one of the most appropriate adaptive capacity systems against sea-level rise.
- ❖ Coastal international roads should be considered as the second protection measure and studies to support them are urgently required.

- ❖ Coastal protection construction need regular maintenance and should be considered in any management plan for coastal zones.
- ❖ Decision-makers in coastal governorates as well as concerned ministers should be aware of the importance of sand dunes systems and their role in protecting the coastal zone of the Nile Delta.

El Raey (2011) concluded that the Nile Delta region is highly vulnerable to potential impacts of climate change especially to sea-level rise and salt water intrusion. The potential impact on water, coastal and agricultural resources is formidable and losses of world cultural heritage cannot be estimated. This calls for immediate and serious action. In particular the following aspects need to be carried out:

- ➢ It is necessary to establish a virtual centre for integrating research activities, carrying out integrated vulnerability assessment, building up a geographic data base of climatic indicators and establishing a regional circulation model.
- ➢ An improvement of the resilience of the population should be carried out through upgrading of infrastructure, building capacities for monitoring and assessment and upgrading awareness of decision-makers, civil society and the population at large.
- ➢ Proactive strategic plans of development should be identified and enforced for all sectors in view of potential impacts of climate change.
- ➢ Introducing policies for adaptation to climate change in various developmental plans, especially in large scale national projects.
- ➢ Recent suggestions of increasing scenarios of sea level rise will make the situation even worse and call for even faster action.

International responses to the impacts of SLR on Egypt

The problem of climate change is being taken seriously by the Egyptian authorities. Low lying land in the Nile delta region is considered to be especially at risk from the effects of any SLR resulting from global warming. In particular, the cities of Alexandria, Rosetta, and Port Said, which are major industrial and economic centres, are expected to experience serious environmental impacts, if no action is taken (***El-Raey, 1999***). In the coastal city of Alexandria, authorities are spending US$ 300 million to construct concrete sea walls to protect beaches from rising seas. Furthermore, Egypt’s Ministry of State for Environmental Affairs (MSEA) is preparing a "National Strategy Study" on adaptation, including a vulnerability index to pinpoint the most endangered regions. Furthermore, The Egyptian Environmental Affairs Agency (EEAA) mentioned that several measures could be utilized to deal with the impact on the coastal zone corridor, including beach nourishment (deposition of sand onto the beach), construction of breakwaters, setting regulations to restrict development in vulnerable areas, changes in land use and Integrated Coastal Zone Management (ICZM), which embraces the general principles of environmental management adopted by United Nations Conference on Environment and Development (UNCED (***El-Raey, 2009***).

The Egyptian government is taking several actions in cooperation with global communities to protect the risked areas and to decrease the effects of the climate change by serious research work and setting new environmental regulations. It has been stated that the Egyptian government had been working for the past 30 years on sea erosion reduction and shore protection measures, particularly by constructing dams in the Nile delta. Furthermore, institutional water bodies in Egypt are working to achieve targets by 2017 through the National Improvement Plan which aims to impede some of the negative impacts of SLR on water resources. It has planned to improve water sanitation coverage for urban and rural areas, develop wastewater management, and optimize the use of water resources by improving irrigation efficiency and agriculture drainage-water reuse (***Bates, 2008***).

According to El-Raey, who criticized that the contingency plans suggested by the government aim to protect the tourism industry in the first place but are not directly related to the impact of climate change and SLR. He stated that additional adaptation measures are needed to target climate change and that this will be less expensive for the tourism industry than losing the beach completely. He mentioned that for Egypt to mitigate and adapt to the effects of SLR, the Egyptian government will have to respond effectively to the following urgent needs; establishing a strong coastal monitoring, assessment and law enforcement system hence identifying and protecting vulnerable areas. In addition to the need for activating ICZM Committee and incorporating of the climate change component in the EIA, promoting awareness and community resilience, and creating new opportunities at safe areas (***El-Raey, 2009***)

Under the provisions of the United Nations Framework Convention on Climate Change (UNFCCC), some work has begun on National Adaptation Programmes of Action (NAPAs). These are intended to facilitate the identification of priority activities, including adaptation to SLR, for the least-developed countries. To date however, only 8 countries have developed comprehensive NAPAs, unfortunately, Egypt is not amongst them. The adaptation science agenda is suggested to have two primary goals; one is to generate and provide scientific knowledge, working in partnership with decision-makers and other stakeholders that can be used to decide and implement vulnerability reducing adaptations. A second goal is to build capacity and partnerships for generating, evaluating, integrating, communicating, and applying knowledge for adaptation. The world has not previously faced a crisis on this scale, and planning for adaptation has to begin instantaneously (***El Sharkawy et al. 2009***).

4.11 *Impact of climate change on crop production in Egypt*

Globally, agricultural emissions have increased by 14% from 1990 to 2005 with an average annual emission of 49 Mt CO_2 eq. yr^{-1} (***US-EPA, 2006***). N_2O from soils and manure management and CH_4 from enteric fermentation were the agricultural sources, showing the highest increase in emissions at 21, 18 and 12%, respectively. N_2O emissions increased by 31 Mt CO_2 yr^{-1}, which is almost twice the rate of increase for CH_4 emissions. US-EPA forecasts acceleration in the global GHG emissions from agriculture for the period 2005–2020. In the developing countries, the growth is expected to continue at the same rate as in 1990–2005, whereas in the more developed regions, the decreasing trend would be reversed and emission would grow by 8% up to 2020 (***US-EPA, 2006***). Two most significant sources, N_2O from soils and CH_4 from enteric fermentation, would also increase quite rapidly. N_2O emission, which is expected to an average of 49 Mt CO_2 yr^{-1}, would continue to grow faster than CH_4 emissions, projected to an average of 35 Mt CO_2 yr^{-1} (***Adhya et al. 2009***).

Specific management options can be used to reduce agriculture's environmental impacts. Conservation practices, that help prevent soil erosion, may also sequester soil C and enhance CH_4 consumption. Managing N to match crop demands can reduce N_2O emission, while manipulating animal diet and manure management can reduce both CH_4 and N_2O emission from animal husbandry. Thus, all segments of agriculture have the management options which can reduce agriculture's GHG footprints. Opportunities for mitigating GHGs in agriculture can be grouped into three broad categories based on the following principles:

- ***Reducing emissions*****:** The fluxes of GHGs can be reduced by managing more efficiently the flows of carbon and nitrogen in agricultural systems. The exact approaches, that best reduce emissions, depend on local conditions and therefore, vary from region to region.
- ***Enhancing removals*****:** Agricultural ecosystems hold large reserves of C, mostly in soil organic matter. Any practice, that increases the photosynthetic input of C or slows the return of stored C via respiration, will increase stored C, thereby 'sequestering' C or building C 'sinks'.
- ***Avoiding emissions*****:** Using bioenergy feed-stocks would release CO_2-C of recent origin and would, thus, avoid release of ancient C through combustion of fossil fuels. Emissions of GHGs can also be avoided by agricultural management practices that forestall the cultivation of new lands (**Tables 4.10, 4.11 and 4.12;** ***Adhya et al. 2009***).

Table 4.10: Shape of different sectors in total anthropogenic GHG emission in 2004 in terms of CO_2 equivalents (adapted from ***IPCC, 2007***)

Sector	Total anthropogenic GHG emission (%)
Energy supply	25.9
Forestry	17.4
Agriculture	13.5
Transport	13.1
Residual and commercial building	7.9
Waste and wastewater	2.8

Table 4.11: Proposed measures for mitigating GHG emissions from agricultural ecosystems and their apparent effect on reducing emissions of individual gases (adapted from ***Adhya et al. 2009***)

Mitigation measures	Processes	Mitigative effects		
		CO_2	CH_4	N_2O
Cropland management	Agronomy	+		±/–
	Nutrient management	+		+
	Tillage/residue management	+		±/–
	Water management(irrigation/drainage)	±/-	+	+
	Rice cultivation		+	±/–
	Agroforestry	+		±/–
	Land-use change	+	+	+
Pasture land management	Grazing intensity	± /-		±/–
	Fertilization	+		±/–
	Nutrient management	+		±/–
	Range fire	+		±/–
	Species introduction	+		±/–
Organic soil management	Avoid drainage of wetlands	+	–	±/–
	Erosion control, organic amendments, nutrient amendment	+		±/–
Livestock management	Improved feeding		+	
	Dietary additives		+	
	Animal breeding		+	
Manure management	Improved storage and handling		+	±/–
	Anaerobic digestion		+	±/–
	Efficient use as nutrient source	+		±/–
Bioenergy	Energy crops, residues	+		±

Note: '+' denotes reduced emission or enhanced removal (positive mitigating effect), '–' denotes negative mitigating effect, '±/–' denotes uncertain or variable effect.

Table 4.12: List of practices to improve fertilizer and manure N-use efficiency in agriculture and expected reduction of N_2O emissions assuming global application of mitigation practices (adapted from ***Mosier et al. 1998***)

Practice followed	**Estimated decrease in**	
	N_2O emissions ($Tg\ yr^{-1}$)	**Field potential**
1. Match N supply with crop demand	0.24	~ 50%
• Use soil/plant testing to determine fertilizer N needs		
• Minimize fallow period to limit mineral N accumulation		
• Optimize split application schemes		
• Match N application to reduce production goals in region of crop over-production		
2. Tighten N flow cycle	0.14	~ 80%
• Integrate animal and crop production systems in		
• terms of manure reuse in plant production		
• Maintain plant residue N on the production site		
3. Use advanced fertilization techniques	0.15	~ 50%
• Controlled release fertilizers		
• Place fertilizers below the soil surface		
• Foliar application of fertilizers		
• Use nitrification inhibitors		
• Match fertilizer type to seasonal precipitation		
4. Optimize tillage, irrigation and drainage	0.15	~ 40%

Agriculture in Egypt is expected to be especially vulnerable because of hot climate. Further warming is consequently expected to reduce crop productivity. These effects are exacerbated by the fact that agriculture and agro-ecological systems are especially prominent in the economics of Egypt as one of the African countries. The rapid growth of the country’s population, the economic stress of reliance on food imports, and the limited area for agriculture requires finding new ways to increase agricultural productivity in general and oil crops in specific. If climate change as projected by atmospheric scientists adversely affected crop production, Egypt would have to increase its reliance on costly food imports.

The potential impact of climate change on some field crops production and ET in Egypt was studied through DSSAT3 and DSSAT3.5 (***Tsuji et al. 1995, 1998***), and COTTAM (***Jackson et al., 1988***) models, (***El-Shaer et al. 1997; El-Marsafawy et al. 2007; El-Marsafawy 2007***). Based on the mentioned previous simulation studies, climate change could decrease national production of many crops (ranging from -11 % for rice to -28 % for soybean) by the year of 2050 compared to their production under current conditions. Yield of cotton would be increased in comparison with current climate conditions. At the same time, water consumptive use for summer crops will be increased up to 8 % for maize and up to 16 % for rice by the year 2050 compared to their current water consumption (***El-Marsafawy, and El- Samanody, 2009***).

To investigate the impacts of climate change on sunflower productivity, water consumptive use, crop water productivity, farm net return and how to mitigate the potential effects of climate change on this crop **El-Marsafawy, and El- Samanody (2009**) studied the economic impacts of future climatic changes on sunflower crop in Egypt. They concluded that, climate change could decrease sunflower seed yield by 27 %, increase water consumptive use by 12 % and decrease crop water productivity accordingly by 34 %. Changing sowing date of sunflower from 1^{st} to 10^{th} of June to 1^{st} to 10^{th} of May could increase seed productivity about 13-18 %. Reducing irrigation water amounts by 10 % could be recommended as a way to conserve irrigation water without clear reduction in seed yield. Climate change without adaptation studies could decrease farm net return about 44 and 63 % for holders who own the land, and holders who rent it, respectively. At the same time, climate change could decrease the economic return from the water unit about 35 %.

4.12 *General Conclusions*

The most significant factors for heat stress-related yield loss in crops include shortening of developmental phases induced by high temperature, reduced light perception over the shortened life cycle and perturbation of the processes associated with plant carbon balance (***Barnabás et al. 2008***). It has been suggested that higher temperatures reduce net carbon gain by increasing plant respiration more than photosynthesis. In fact, the light-saturated photosynthesis rate of C_3 crops such as wheat and rice is at a maximum for temperatures from about 20–32 °C, whereas total crop respiration shows a steep nonlinear increase for temperatures from 15 to 40 °C, followed by a rapid and nearly linear decline ***(Porter and Semenov, 2005)***. Increased temperature could potentially reduce photosynthetic capacity due to the heat lability of Rubisco activase on the one hand and the limitation of electron transport in the chloroplast on the other hand (***Sage et al. 2008***). In addition, by increasing the air evaporative demand, higher temperatures are often implicated with stomatal closure, which further decreases photosynthesis due to smaller CO_2 flux into leaves. The CO_2:O_2 ratio at the active site of Rubisco is about 0.024, and therefore the relative rate of carboxylation to oxygenation is ca. 2.2 at 25 °C, implying that about every third molecule of RuBP is consumed in photorespiration. Rising temperature modifies the kinetic constants of Rubisco, increasing the rate of oxygenation more than that of carboxylation, in addition to lowering the solubility of CO_2 relative to O_2. As a consequence, the rate of carboxylation to oxygenation is reduced (increased photorespiration rates) even further, about 1.4 at 35 °C (***Ainsworth and Rogers, 2007***), thus further compromising the plant carbon balance at elevated temperatures (**Figure 4.15**; ***Da Matta et al. 2010***).

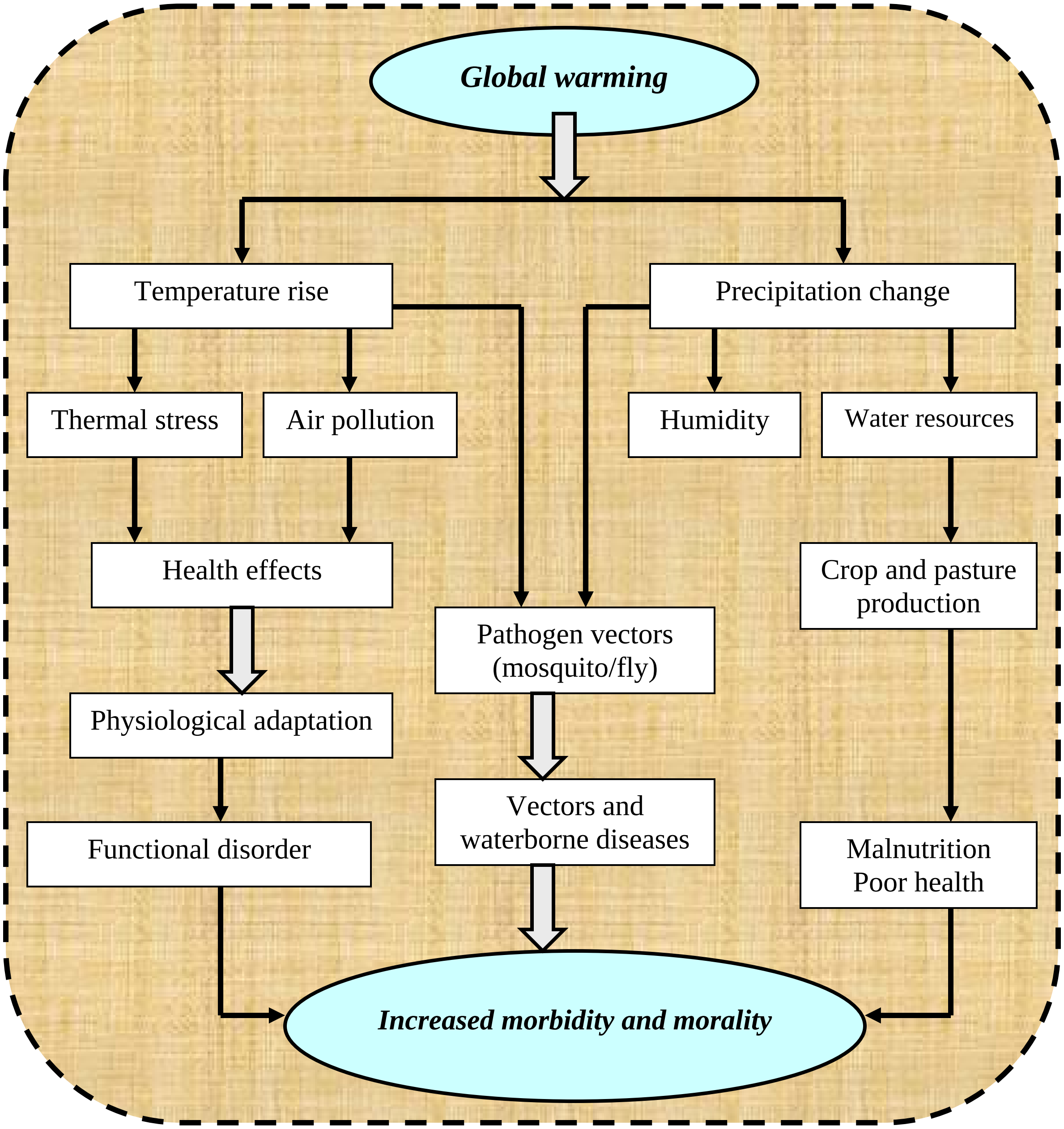


Figure 4.15: Impact of global warming on human and animal diseases (adapted from ***Mavi and Tupper, 2004***)

Some evidence indicates that elevated [CO_2] can offset the negative impacts of high temperatures on photosynthesis and crop growth and production (***Polley, 2002***), depending on warmer baseline climates. Nevertheless, it must be emphasized that the effects of high [CO_2] and temperature on plants often are not additive, implying that the combined effects of these changes cannot be predicted from knowledge of their individual effects. In addition, it seems that the magnitude and even direction of crop responses to elevated [CO_2] and temperature change are species and even cultivar-specific (***Polley, 2002***). In summary, the predicted increase in average global temperature will accelerate crop development rates, and the negative effects tend to be larger for grain yield than for total biomass (***Fuhrer, 2003***). These constraints associated with other ongoing climatic changes such as more frequent and severe droughts and more intense precipitation events will probably offset gains in carbon assimilation associated with elevated CO_2 (***Sage et al. 2008***).

Despite there being a growing body of evidence suggesting that C_3 crops are likely to produce more harvestable products and that both C_3 and C_4 crops are likely to use less water with rising atmospheric [CO_2] in the absence of stressful conditions, large uncertainties remain about food production in a future scenario with global warming and altered regional patterns of precipitation. In addition, there is currently a limited ability to include realistic impacts of pests and diseases in a changing climate, which otherwise would be an essential aspect for future food security. In fact, both chemical and microbiological risks are foreseen to impair food and feed safety as a consequence of climate change: in particular, mycotoxins, pesticide residues, trace metals and other chemicals could affect food and feed safety. There is, therefore, an urgent need for scientific research that can improve our understanding of the interactions of rising atmospheric [CO_2] with other environmental variables, such as temperature, water supply and ozone concentration, as well as with biotic factors such as pests and diseases, under real field conditions. In doing so, it is necessary not only to quantify the effects of climatic changes on crop production but also on food quality. It is also necessary to assess responses of crops other than the key cereal grains, and in climate regions other than temperate ones, notably those of importance to developing countries in the tropics and subtropics. Furthermore, since distinct varieties seem to respond differently to elevated CO_2 and temperature in terms of harvestable yield, future research should be also directed towards selecting promising genotypes for a changing global climate (***Da Matta et al. 2010***).

Greater effort to increase the availability and applicability of climate change adaptation options for conservation—through concrete strategies and case studies illustrating how and where to link research agendas, conservation programs and institutions—is badly needed. There is a need for dialog and cooperation among the Nile Basin states to address both technical issues such as sharing of data, as well as more political and sensitive ones such as water allocation. It could be argued that the best response for Egypt might be to insist on status quo and not agree to any reallocation which will inevitably decrease the share of Nile flows into Egypt. However, over the long term a co-operative mechanism to resolve water sharing issues could also be in Egypt’s interest, as it would reduce the risk of uncertainty and surprise. A co-operative regime might also engender exploration of linked adaptations across the boundaries of the riparian countries whereby water allocation is linked to trade in water intensive commodities such as hydroelectricity and food products (***Agrawala et al. 2004***). The recently established Nile Basin Initiative is therefore a step in the right direction. However, it is too early to assess the effectiveness of the NBI, given that it has been in existence for only a few years. Nevertheless, it marks an important beginning in terms of providing a cooperative forum to reconcile the water needs, development aspirations, and climate change concerns, not only of Egypt but of all the Nile Basin countries.

Although GHG emission derived from soil has been researched for several decades, there are still geographic regions and agricultural systems that have not been well characterized. There is an urgent need to estimate GWP across a wide range of agricultural systems. Ideally, a standard or benchmark method to calculate GWP should be established. Methodology to improve the accuracy of determining changes in SOC and GHG emissions would reduce the uncertainty of estimating GWP. Similarly, farmers' participation appears indispensable for technology transfer of any kind, including management changes aimed at sustainable production systems. It is essential to initiate dialogue with the farmers and other stakeholders about GHG concerns and the agricultural practices that would help in mitigating the menace, through various routes:

- Improving the understanding of farmers' perceptions and decision making to classify different target groups for specific mitigation strategies.
- Conducting research on farmers' fields or community areas (instead of research stations) as a 'reality check' for suggested improvements.
- Developing alternative management options in close collaboration with farmers preferably derived from indigenous knowledge on sustainable management practices.
- Focusing on farm households rather than individual production systems and evaluating the economic benefit to the farmer, e.g. affordability versus profitability.
- Packaging scientific knowledge in practical and user-friendly forms through easy decision-support tools.
- Establishing continuous feed-back on mitigation strategies over longer time spans, e.g. farmers' perception on water pricing may vary according to weather events.
- Educating farmers and rural communities by knowledge initiatives (***Adhya et al. 2009***).

5 *References*

Nothing more than ***books*** and I wish I were able to love books more than you love for your mother and would like to warn you a sense of beauty!!

— Native Pharaonic proverb

We *will know only what we are* ***taught****;*
We will be ***taught*** *only what others deem is important to know;*
And we will ***learn*** *to value that which is important.*
— Native American proverb

What *is common to the greatest number gets the least amounts of care.*
Men *pay most attention to what is their own:*
They *care less of what is common.*
— Aristotle

The most important websites for climate change:

Intergovernmental Panel on Climate Change (www.ipcc.ch)
United Nations Framework Convention on Climate Change: (www.unfccc.int)
United Nations Environment Programme: (www.unep.org)
UNEP/GRID-Arendal: (www.grida.no/climate)
Climatewire (a climate news portal): (www.climatewire.org)
The Climate Data Online site (www.ncdc.noaa.gov/oa/climate/climatedata.html)
The National Climatic Data Center (NCDC, www.ncdc.com)

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