SOLAW TR04A

Land and water use options for climate change adaptation and mitigation in agriculture

SOLAW Background Thematic Report - TR04A

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Abbreviations and acronyms

BNF	Biological nitrogen fixation
C	Carbon
CDM	Clean Development Mechanism
CH4	Methane
CO_2	Carbon dioxide
FR	Forest restoration
GCF	Green Climate Fund
GEF	Global Environmental Facility
GHGs	Greenhouse gases
ha	Hectare
IEA	International Energy Agency
IFES	Integrated Food Energy Systems
INM	Integrated nutrient management
JI	Joint implementation
kg	Kilogram
LCA	Life cycle analysis
LULUCF	Land use, land-use change and forestry
Mb/d	Million barrels per day
Mtoe	Million tonnes of oil equivalent
N	Nitrogen
N2O	Nitrous Oxide
NAPA	National Adaptation Programmes of Action
NPP	Net primary productivity
NT	No-till
R&D	Research and design
REDD+	Reduced deforestation and degradation of tropical forests
RMPs	Recommended management practices
SBI	Subsidiary Body for Implementation
SFM	Sustainable forest management
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
UNFCCC	United Nations Framework Convention on Climate Change
yr	Year

Executive summary

There is much concern about the impact of climate change on land and water resources, and the implications for agricultural production worldwide. Indeed, the United Nations Framework Convention on Climate Change (UNFCCC), which aims to prevent 'dangerous anthropogenic interference' with the climate system, lists food security prominently among the human activities and ecosystem services that are seriously threatened by climate change. Thus planning and funding of adaptation strategies that aim to increase the resilience of agricultural systems in the face of increasing climate threats, especially in poor developing countries, which are already at the margins of production, is a centrepiece of the current post-Kyoto debate.

At the same time, it is recognized that agriculture and forestry offer significant cost-effective mitigation options, since many management techniques, are required to strengthen production systems, sequester carbon either above or below ground and reduce direct greenhouse gas emissions. Therefore, the serious challenges to agriculture caused by climate change also offer opportunities to devise and fund a range of land management strategies having positive adaptation and mitigation synergies. These new trends will shape domestic and international policies, trading patterns, resource use, regional planning and the welfare of rural people especially in developing countries.

Current research confirms that while crops may respond positively to elevated CO_2 in the absence of climate change, the associated impacts of high temperatures, altered patterns of precipitation, and possibly increased frequency of extreme events, such as drought and floods, will likely combine to depress yields and increase production risks in many regions, thus widening the gap between rich and poor countries ([1.1]; [1.2]; [1.3]). A consensus has emerged that developing countries are more vulnerable to climate change than developed countries, because of the predominance of agriculture in their economies, the scarcity of capital for adaptation measures, their warmer baseline climates, and their heightened exposure to extreme events. Thus climate change may have particularly serious consequences in the developing world, where about 800–1 000 million people are currently undernourished.

Many interactive processes determine the dynamics of world food demand and supply: agroclimatic conditions, land resources and their management are clearly a key component, but they are critically affected by distinct socio-economic pressures, including population growth patterns, availability and access to technology and development and demand for bio-energy [1.4]. In the last three decades, for instance, average daily per capita intake has risen globally from 2 400 to 2 800 calories, spurred by economic growth, improved production systems, international trade and the globalization of food markets. Feedbacks of such growth patterns on cultures and personal taste, lifestyle and demographic changes have led to major dietary changes – mainly in developing countries, where shares of meat, fat and sugar to total food intake have increased significantly [1.3].

Bio-energy production, in particular liquid biofuels for transportation, has already begun to compete with food production over land and water resources; its share within global energy supply is expected to increase dramatically in coming decades. Concerns about impacts on food security, net overall greenhouse gas (GHG) emissions savings, and environmental sustainability of production, however, have led many countries to reassess their short-term production targets. This is particularly true for 'first generation' liquid biofuels, i.e. those obtained from dedicated energy crops such as maize and sugar cane. Potential negative impacts on cropland and food security may be reduced by the introduction of second-generation liquid biofuels, derived from biomass waste, which may constitute a quarter of biofuels supply by the next decade [1.4].

Several integrated assessment studies have focused on quantifying the key impacts of climate change on food production, as a function of different socio-economic scenarios, including the analyses of likely adaptation strategies such as changes in crop management and economic adjustments ([2.1]). As society learns to respond to the pressures of climate change over the coming decades, clearly to minimize the negative impact of climate on human activities and ecosystems, adaptation strategies will need to be implemented together with mitigation activities [2.2].

The benefits of adaptation of land and water management are most pronounced with low to moderate warming. This effective response has been characterized as 'buying time', i.e. a way to provide successful, albeit temporary, coping strategies to reduce production losses in coming decades. Autonomous adaptation actions are defined as responses to be implemented by individual farmers, rural communities and farmers' organizations, depending on perceived or real climate change in the coming decades, and without intervention or coordination by regional and national governments and international agreements.

To this end, maladaptation, for example pressure to cultivate marginal land, or adopt unsustainable cultivation practices as yields reduce, may increase land degradation and endanger the biodiversity of both wild and domestic species, possibly jeopardizing future ability to respond to increasing climate risk later in the century. In particular, several autonomous response strategies may place extra stress on water and other environmental resources as warming increases. Planned adaptation, including changes in policies, institutions and dedicated infrastructure, will therefore be needed to facilitate and maximize the long-term benefits of adaptation responses to climate change [2.1].

Several adaptation activities, leading to the increased resilience of systems and improved rural incomes, may be attractive to carbon markets because of their associated mitigation value. No-regrets, win-win strategies that provide additional income to poor rural communities may, for instance, include forestry management and agroforestry techniques, agricultural 'good practices' that conserve soil and water resource; and properly scaled bio-energy projects for rural communities. As climate changes, as well as socio-economic pressures, future demands for food will be influenced. Thus, fiber and energy synergies will need to be identified among adaptation and mitigation strategies, so that robust options for land and water management can be developed to meet both climate and societal challenges of the coming decades. Ultimately, farmers and others in the agricultural sector will be faced with the dual task of contributing to global reductions of carbon dioxide and other greenhouse gas emissions, while having to cope with an already changing climate [2.3].

To this end, the Bali roadmap, the Copenhagen Accords and the Cancun Agreements provide an important focus on the synergies between adaptation and mitigation strategies, offering a unique window of opportunity for developing countries to identify, negotiate and take advantage of enhanced and additional financial resources that could be used to help the rural poor reduce their vulnerability to climate change. Under the current financing mechanisms of the Kyoto Protocol, particularly the Clean Development Mechanism (CDM, Joint Implementation (JI) and the Global Environmental Facility (GEF) Adaptation Fund, significantly larger financial flows could be directed to helping developing countries by focusing on the agriculture and forestry sectors, which are often the main source of employment and income [2.4].

Developing countries will need about US$100 billion per year by 2030 to adjust to climate change and minimize risk. Some of these financial flows could be generated by including more agriculture and forestry within regulated carbon markets. Without such inclusion and significant scaling up, the future income from current CDM activities in agriculture and land use, land-use change and forestry (LULUCF) sectors could supply no more than US$1–10 billion in carbon funding to developing countries, i.e. it would fall short by at least an order of magnitude for the stated adaptation needs. There is therefore a significant gap between the level of funding needed for adaptation to climate change in poor developing countries, and the carbon funding level foreseen under the UNFCCC flexible mechanisms. Additional recent funding for adaptation and mitigation) is an attempt to bridge part of this gap [3.5].

There is scope for enhancing carbon offsets from agriculture and forestry, by both strengthening the numbers of these project categories, scaling up related activities and widening their geographic distribution. Importantly, the economic potential for additional carbon sequestration from these activities — including reduced deforestation and forest degradation, sustainable forest management actions, agroforestry techniques, soil conservation in agriculture and renewable energy from biomass — is substantial. The annual financial flows from these offsets could be as high as US$20–100 billion in 2030, decisively helping to meet the expected costs of adaptation to climate change in developing countries [3.5]. Specific activities could be supported through monetization of both their mitigation and adaptation components, i.e. through the development of special carbon credits, validated under a novel 'adaptation carbon' standard. These credits could be supported in part on the voluntary market, but especially in regulated post-Kyoto markets, for instance by requiring compliance buyers to include a percentage of such credits into their portfolios [3.5].

In conclusion, significant financial flows could be generated by including a range of agricultural and forestry activities within post-2012 climate mechanisms. These flows would help support sustainable rural development and provide much needed funding for sound adaptation responses in developing countries.

1. Trends and projections: anticipated impacts of climate change on land and water use for agriculture

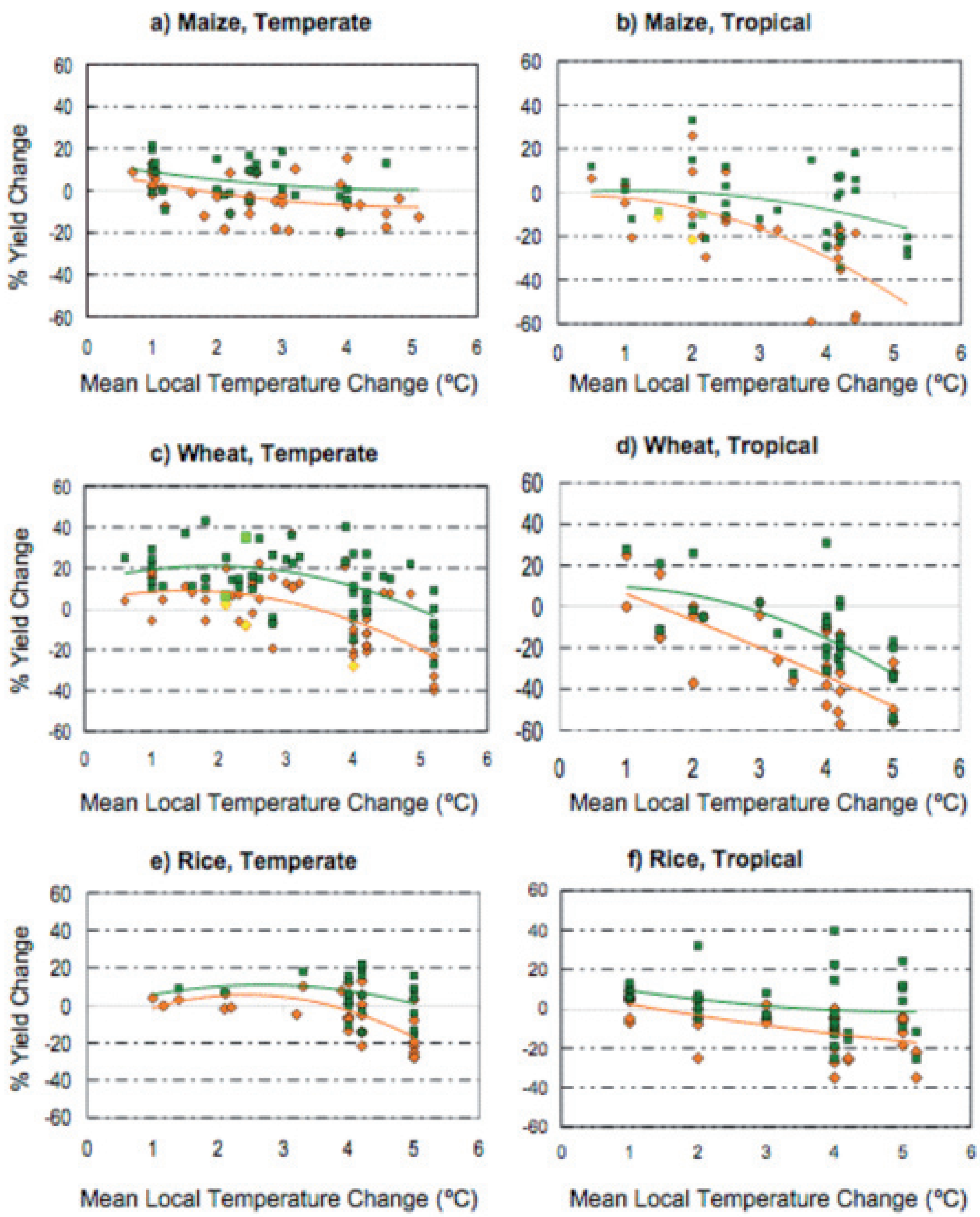
1.1 State of the knowledge (by region)

Expected changes in the mean and variability of temperature and precipitation, elevated CO_2, plus complex interactions among these, will lead to region-specific impacts land and water resources, greatly affecting crop productivity and the agricultural sector in the coming decades.

Temperature

The Fourth Assessment Report of the IPCC (Easterling *et al*., 2007) suggests that moderate warming, i.e. in the first half of this century, may benefit crop and pasture yields in temperate regions, while it would decrease yields in semi-arid and tropical regions. Modelling studies indicate small beneficial effects on crop yields in temperate regions corresponding to local mean temperature increases of 1–3 ºC and associated CO_2 increase and rainfall changes. In contrast, in tropical regions, models indicate negative yield impacts for the major crops even with moderate temperature increases (1–2 ºC). Further warming projected for the second half of the twenty-first century has increasingly negative impacts in all regions (Figure 1).

FIGURE 1: SENSITIVITY OF CEREAL YIELD TO CLIMATE CHANGE



Sensitivity of cereal yield to climate change for maize, wheat and rice, as derived from results at multiple simulation sites, against mean local temperature change used as a proxy indicating magnitude of climate change in each study. Responses include cases without adaptation (orange dots) and with adaptation (green dots). Adaptation represented in these studies included changes in planting, changes in cultivars, and shifts from rainfed to irrigated conditions.

Source: IPCC (2007)

Precipitation

Changes in precipitation regimes, including changes in mean and distributions, will be critical to soil–water status and thus to crop productivity, particularly through joint changes with temperature that affect evaporative demands. Projections for crop impacts however significantly depend on the precipitation scenario considered. This is because more than 80 percent of total agricultural land, and close to 100 percent of pastureland, is rainfed, GCM-projected changes in precipitation will often shape both the direction and magnitude of the overall impacts. In general, changes in precipitation, and more specifically in evapotranspiration to precipitation ratios, modify ecosystem productivity and function, particularly in marginal areas; yet higher water-use efficiency as a result of stomatal closure and greater root densities under elevated CO_2 may in some cases alleviate or even counterbalance drought pressures. Although the latter dynamics are fairly well understood at the single plant level, the implications for whole ecosystems are not understood (Tubiello *et al*., 2007).

Extreme events

Future climate change conditions are likely to be characterized by increased frequency of extreme events, such as heat waves, hail storms, excessive cold, heavy and prolonged precipitation and droughts, with negative impacts on crop yields. Extreme weather events such as heavy rain, hail storms and flooding can physically damage crops, while extremely wet conditions in the field can delay planting or harvesting. Prolonged droughts lead to outright crop failure. Compared to scenarios that only consider mean climate change, increased frequency of extreme events may lead to unexpected, earlier and larger impacts on agriculture with significant consequences for food production (FAO, in press). Therefore preparing agricultural systems to withstand increased climate variability is an essential component of appropriate adaptation responses (Rosenzweig *et al*., 2002), as discussed in detail in the following sections.

Water resources

Impacts of future climate change on freshwater supply are expected to be significant, with projected increases in water-stress already pronounced by 2050 in many regions. From the viewpoint of agricultural, critical regions and irrigation water management systems at risk from climate change include (FAO, in press):

- large surface irrigation systems fed by glaciers and snow melt—most notably northern India and China;

- large deltas, where sea level rise will increase flood and storm cyclone damage, as well as increase the risk of salinity intrusion;

- surface and groundwater systems in arid and semi-arid regions, where rainfall will decrease and become more variable;

- humid tropics: seasonal storage systems in the monsoon regions, where the proportion of storage yield will decline, but peak flood flows are likely to increase; and

- all supplemental irrigation areas where the consequences of irregular rainfall are mitigated by short-term interventions to capture and store more soil moisture or runoff. This comprises the temperate regions in Europe and North America, which may experience seasonal drying even with increased annual rainfall; and the Mediterranean and seasonally arid regions (Figure 2).

FIGURE 2A: MAIN AGRICULTURE WATER MANAGEMENT SYSTEMS THAT MAY BE IMPACTED BY CLIMATE CHANGE

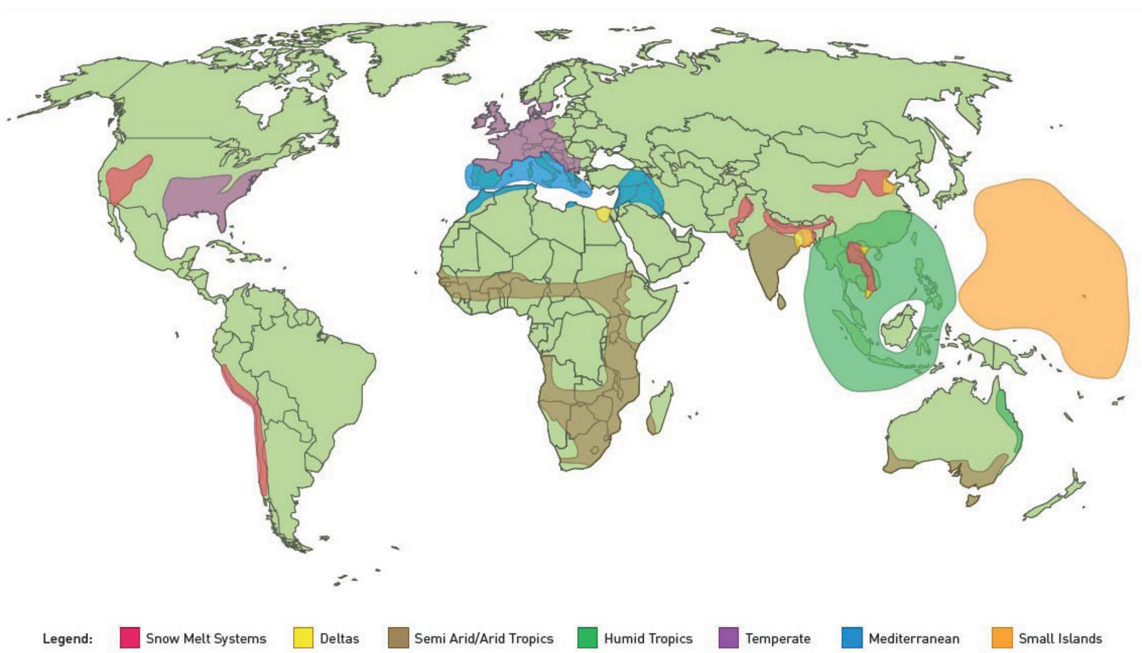
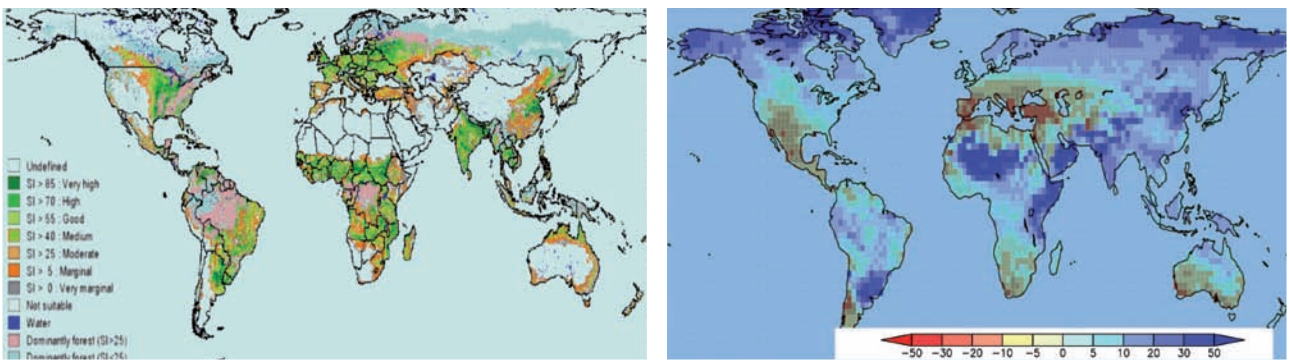


FIGURE 2B: PROJECTED IMPACTS OF CLIMATE CHANGE ON AGRICULTURE AND WATER RESOURCES.



Projected impacts of climate change on agriculture and water resources. (Left) Current suitability for rainfed crops; (Right) Ensemble mean percentage change of annual mean runoff between present (1981–2000) and 2100.

Source: IPCC, 2007

Even in areas where there is a projected increase in annual runoff the total water supply may be at risk. This is because this benefit may be counterbalanced by the negative effects of increased precipitation variability and changes in seasonal runoff in water supply, water quality and flood risks. Changes in water quantity and quality resulting from climate change are expected to affect all four dimensions of food security: availability (i.e. production) stability, access and utilization. This is expected to lead to decreased food security and increased vulnerability, especially of poor rural farmers in the arid and semi-arid tropics, as well as in Asian and African mega-deltas (IPCC, 2008).

CO_2 increase

Elevated atmospheric CO_2 levels stimulate leaf photosynthesis and leaf stomatal closure, potentially increasing plant growth and yield and improving the efficiency of plant water use. However, in real agricultural fields, these benefits to crop production are expected to be lower than in CO_2 plant experiments, because of limiting factors such as soil and water quality, water supply, crop-weed competition and infections by pests and diseases. In addition, CO_2/temperature interactions are recognized as a key factor determining plant damage from pests in future decades; CO_2/precipitation interactions will likewise be important.

Agricultural pests and disease

Increases in precipitation and temperature can lead to increased pest and disease pressure on crops and livestock, with changes in overwintering survival, regional distribution, growth rates and outbreaks. Competition between C3 crop and C4 weed species under different climate conditions and CO_2 concentrations may significantly alter crop productivity in coming decades. Adaptive management strategies may lead to a mismatch between enemies and pests in space and time decreasing the effectiveness of biological control.

1.2 Anticipated impact on agro-ecological zones and major food production systems

Rainfed areas (crop suitability and function)

Several studies indicate that rising temperatures will reduce crop yields in many regions, especially where soil, water and climate resources are already limited, including many food insecure countries. Impacts of increased under-nutrition on human health would further compound negative impacts, especially for smallholder, subsistence farmers and pastoralist communities, whose access to good land, adequate agricultural inputs and viable markets is limited (FAO, 2009a). Specifically, without sufficient adaptation measures, South Asia and Southern Africa may suffer negative impacts on staple crops such as maize, wheat and rice. Harvests of rice and maize could fall between 20 and 40 percent as a result of increased temperatures during the growing season in tropical and subtropical regions (Fischer *et al*., 2007). Likewise, increased temperature and water stress is expected to depress cereal yields in the Mediterranean region and in Central Asia. In contrast, developed higher-latitude countries may experience increases in agricultural productivity as a result of a warming climate. Finally, arable lands in coastal regions might be lost owing to sea level rise and flooding, especially in low-lying deltas such as south and Southeast Asia. In coastal regions agricultural soils may be exposed to salinization resulting from saltwater intrusion in the groundwater.

Irrigated areas (including impact on water use)

Over 300 million ha of arable land is under irrigation in the world, using over 2 500 billion m^3 of water annually. This represents 70 percent of the fresh water resources withdrawn for human activity (Fischer et al., 2007; FAO, in press). Irrigation sustains a large portion of world food supply; about 40 percent for cereals. Unsustainable consumption of surface and groundwater for irrigation is already affecting natural water reservoirs around the world.

The impacts of climate change on irrigation requirements will be felt through net changes in precipitation and evaporative demands, including impacts on regional water availability through snow melt, river flow, etc. The latter can be significant. Major changes in precipitation may impact river flow in key irrigated regions, especially the Indian subcontinent (FAO, in press; de Fraiture *et al*., 2007); although these changes may be difficult to quantify. Instead, most studies have focused on changes in irrigation water demand(IPCC, 2008). They project that net crop irrigation requirements, i.e. including local precipitation changes and transpiration losses, may increase 5 to 20 percent globally by 2080, with larger regional signals, for example, +15 percent in Southeast Asia. Greater impact is foreseen in developed versus developing regions, as a result of both increased evaporative demand and longer growing seasons under climate change (Fischer *et al*., 2007). Water stress — the ratio of irrigation withdrawals to available renewable water resources — will likely increase as a result of climate change, especially in the Near East and Southeast Asia. Regional studies have likewise stressed critical climate change and water dynamics in key irrigated areas worldwide. For instance, taking into account changes in precipitation related to climate change, these models predict increased irrigation requirements in North Africa and decreased irrigation requirements in China (IPCC, 2008).

Increased frequency of droughts will stress water reservoirs, as more water will be needed to offset increased crop demand. For instance, irrigation water use increased significantly during the 2003 heat wave in France and helped offset crop losses in regions having a higher percentage of maize irrigation; yet overall yield loss was still considerable.

Forests

Forests cover just over 4 billion ha or 31 percent of land. Of this area, 7 percent is planted forests, but their area is rapidly increasing. Close to 1.2 billion ha of forests (30 percent of the total area) are primarily managed for the production of wood and non-wood forest products. An additional 949 million ha (24 percent) are designated for multiple uses; in most cases including the production of wood (FAO, 2010b). Simulations using yield models show that climate change can increase global timber production through northward expansion of forests and higher growth rates. However regional production will exhibit great variability, similar to that discussed for crops, i.e. early harvest increases before mid-century, followed by reductions in productive area because of greater warming and water stress, especially for softwoods growth.

Climate change may substantially impact other forest ecosystem services, such as seeds, nuts, hunting, resins, plants used in pharmaceutical and botanical medicine and in the cosmetics industry. Recent studies suggest that positive growth impacts on forests affected by climate change will be lower than initially anticipated as a result of a better understanding of the CO_2 response in trees. For instance, while average productivity increases in young trees under elevated CO_2, little overall stimulation in stem growth of older tree stands has been observed. Additionally, factors such as species competition, disturbance, pollutants and nutrient availability, may limit stand-level response to elevated CO_2. For the Amazon, dynamic forest vegetation models have suggested that initial forest losses resulting from climate change may lead to warmer local temperatures and a further weakening of the regional water cycle, setting in motion a vicious cycle (i.e. positive climate feedback) that could lead to significant forest die-back (Philips *et al*., 2009).

Livestock

Livestock health and productivity may be at significant risk owing to projected climate change, especially intensive livestock production systems. In particular, heat stress is known to lower productivity, through declines in animal physical activity with associated declines in eating and grazing in ruminants and other herbivores. New models of animal nutrition have shown that high temperatures may put a ceiling on dairy milk yield, leading to expected severe reductions in the potential of the modern (Friesian) cow breed in the tropics in coming decades. It is expected that as a result of climate change this would affect up to half of the current potential and lead to decreasing cow fertility, fitness and longevity. Increases in air temperature and/or humidity will affect conception rates of domestic animals not adapted to those conditions. This is particularly the case for cattle, in which the primary breeding season occurs in the spring and summer months (IPCC, 2007).

The impact of increased climate variability on animal productivity needs to be considered. Already, severe weather events often result in catastrophic losses in confined cattle feedlots, with major economic losses from reduced cattle performance. In dry regions, there are risks that severe vegetation degeneration may lead to positive feedbacks between soil degradation and reduced vegetation and rainfall, with corresponding loss of pastoral areas and farmlands. Projected temperature increases, combined with reduced precipitation in some regions, e.g. Southern Africa, would lead to increased loss of domestic herbivores during extreme events in drought-prone areas. With increased heat stress in coming decades, water requirements for livestock will increase significantly compared with current conditions so that overgrazing near watering points is likely to expand (IPCC, 2007).

Grassland, pastures and rangelands

Pastures and livestock production systems occur in most climates and range from extensive pastoral systems with grazing herbivores to intensive systems based on forage and grain crops, where animals are mostly kept indoors. The combination of increases in CO_2 concentration, changes in rainfall and temperature, are likely to significantly impact grasslands and rangelands, with production increases in humid temperate grasslands, and decreases in arid and semi-arid regions.

Animal requirements for crude proteins from pasture are between 8–24 percent of ingested dry matter, depending on animal activity and production levels (Tubiello *et al*., 2007). Changes in the composition of grass species caused by climate change will thus impact livestock. For instance, large areas of upland Britain are already colonized by relatively unpalatable plant species such as bracken, matt grass and tor grass, because of recent trends in warmer temperatures. Elevated CO_2 may lead to grass conditions with lower N status, reducing protein availability. On the other hand, increases in the legume content of swards may compensate for the decline in protein content of non-fixing grassland species. The decline under elevated CO_2 of C4 grasses, which are a less nutritious food resource than C3, may compensate for the reduced protein content under elevated CO_2.

In addition, climate change is expected to affect the stability and resilience of plant communities. Experiments suggest the possibility of rapid changes in species composition and diversity under climate change. For instance, elevated CO_2 and nitrogen deposition may decrease plant diversity in Mediterranean-type annual grasslands, while increased precipitation may cause it to increase. Specifically, elevated CO_2 may change the composition of plant species by favoring the establishment of different plant seedlings compared to current conditions.

As discussed, elevated CO_2 is expected to favour legumes both in sown mixtures and within temperate semi-natural grasslands How to extrapolate these findings beyond experimental plots is still unclear, given that: i) factors such as the availability of phosphorus in the soil and herbage use may limit increases seen experimentally; and ii) existing empirical models do not capture key management factors such as grazing, cutting and fertilizer supply. A recent simulation of over 1 000 European plant species predicted that half of these species would become vulnerable or endangered by the year 2080, as a result of rising temperature and changes in precipitation (Soussana *et al*., 2010).

Fisheries

World capture production of fish, crustaceans and molluscs in 2004 was more than twice that of aquaculture, but trends project similar catches in the coming decade (FAO, 2004). Some aquaculture, particularly of plants and molluscs, depends on naturally occurring nutrients and production, but the rearing of fish usually requires the addition of suitable food, mainly obtained from capture fisheries. Negative impacts of climate change on aquaculture and freshwater fisheries include stress, linked to increased temperature and oxygen demand, extreme weather events and rise in sea level; increased ocean acidity related to elevated CO_2 may become a problem in coastal aquaculture. Positive impacts include increased growth rates and food conversion efficiencies, increased length of growing seasons, range expansion and use of new areas because of the potential decrease in ice cover.

Direct effects of increasing temperature on marine and freshwater ecosystems are already evident, with rapid poleward shifts in regions, such as the northeast Atlantic, where temperature change has been rapid. Further changes in distribution and production are expected because of the continuing warming and freshening of the Arctic. Local extinctions are occurring at the edges of current ranges, for example in salmon and sturgeon.

1.3 Implications for the patterns and styles of agricultural production

Many interactive processes determine the dynamics of world food demand and supply: agroclimatic conditions, land and water resources and their management are clearly a key component, but they are critically affected by distinct socio-economic pressures, including current and projected trends in population growth, availability and access to technology and development.

Food production needs to almost double in developing countries by 2050 compared to today if food security is to be addressed seriously in coming decades. Current trends and model simulations indicate that global cereal demand will grow from roughly 2.1 billion tonnes today to about 3 billion tonnes in 2050 (FAO, 2006a). Projections depend on assumed socio-economic drivers, especially on expectations for growth in population and incomes[1]. At the same time, the number of undernourished are expected to decrease in both relative and absolute number by 2080, from current levels of 850–1 000 million to less than 200 million across the range of socio-economic scenarios known as Intergovernmental Panel on Climate Change – Special Report on Emissions Scenarios (IPCC SRES), except for scenario A2, for which the number of people at risk of hunger would remain relatively unchanged by 2080 compared to today.

Resource use is expected to increase alongside increased production, most of it in developing countries. In particular, extrapolation of current trends and expert opinion suggest that irrigated areas will increase by 15–17 percent in 2050 compared to today, with irrigation water withdrawals increasing by 9–11 percent (FAO, 2006a; FAO, 2009b). Models project further increases in irrigation water withdrawals by the end of the century, i.e. by 21 percent in 2080 compared to current levels, as a result of increases in irrigated land of up to 100 million ha (Fischer *et al*., 2005; 2007). Finally, roughly 120 million ha of additional land (+27 percent), most of it in Africa and Latin America, are thought necessary by 2050 compared to today (FAO, 2006a; 2009b), and as much as 250 million ha by 2080 (Tubiello and Fischer, 2007).

Considering these assessments, global land water and crop resources, together with technological progress appear, in principle, to be sufficient to feed a world population of about 9 billion people (13 billion in A2) in 2080 (Fischer *et al*., 2005). However, large uncertainties remain about degrading land and water resources in developed countries and especially in developing regions, particularly for food security. In particular, reduction of world hunger, albeit significant in projections to the end of the century, is expected to be small until 2030 globally and perhaps until 2040 for sub-Saharan Africa. This implies that Millennium Development goals,

[1] IPCC SRES scenarios are typically employed in integrated assessment analysis. They refer to four plausible development paths, from high-emission scenarios such as A1 (business as usual) and A2 (high population growth rates), to lower emission cases such as B2 and B1. Results associated to these scenarios are presented in a range – the lower and higher limits corresponding to B1 and A2, respectively. The A2 scenario is considered too extreme in terms of projected population, although it provides a useful upper limit to projections of food demand.

i.e. halving world hunger by 2015, will be difficult to meet without additional targeted actions and mechanisms, including perhaps carbon markets, as discussed in later sections (Schmidhuber and Tubiello, 2007).

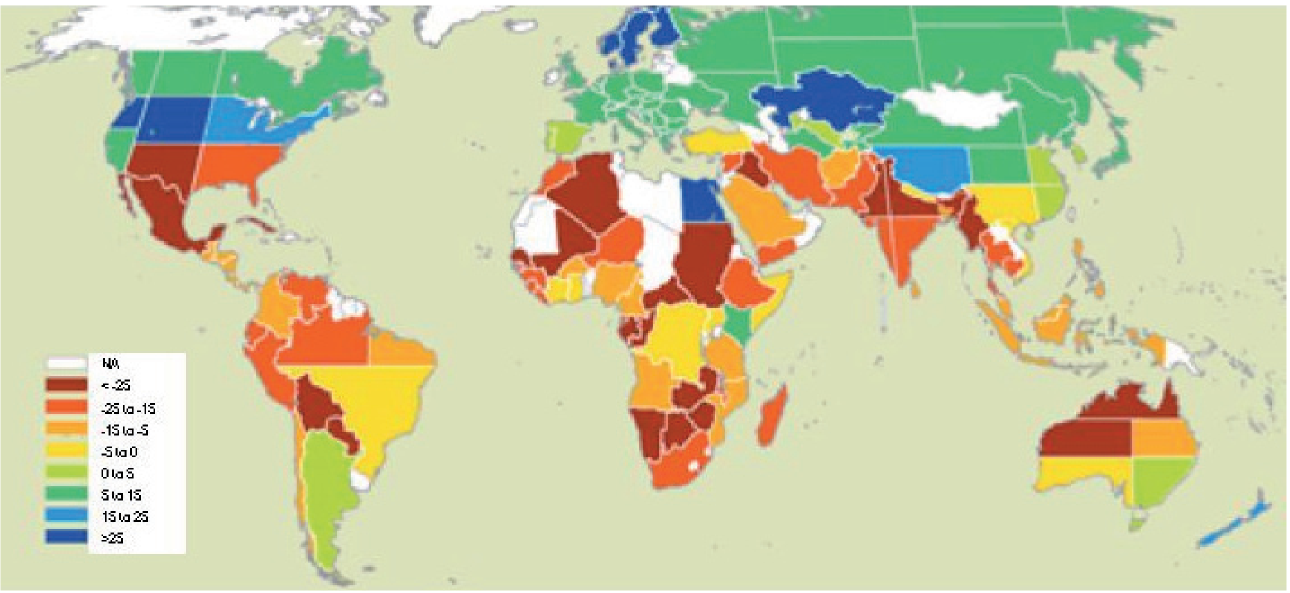
At global level

Climate change will add a significant set of challenges to agriculture and its underlying land and water resources. The IPCC indicates that, although crops would respond positively to elevated CO_2 in the absence of climate change, the associated impacts of high temperatures, altered patterns of precipitation, and possibly increased frequency of extreme events such as drought and floods, will likely combine to depress yields and increase production risks in many world regions, widening the gap between rich and poor countries.

Integrated models of agroclimatic and socio-economic dynamics, have thus far been unable to account quantitatively for the potentially very negative impacts of increased climate extremes, pest and disease infection. Assessing only the impacts of mean changes in temperature and precipitation variables, they tend to find small to no changes in the potential of global food production, regarding a baseline without climate change, especially up to the middle of this century. There are, however, significantly more negative impacts on production over time, especially in developing regions. Typically, the impacts of climate change on world aggregate cereal production, depending on the scenario considered, vary between -2 and +2 percent (IPCC 2001; 2007).

Regional and temporal patterns of these impacts are far more diverse and significant. First, small global reductions tend to mask opposite impacts on developed and developing regions. Specifically, in 2080, production tends to increase in developed countries and decrease in developing regions (Figure 3). At times symmetries can be significant, for instance up to +9.0 percent gains in developed and with 7.2 percent losses in developing regions, indicating significant absolute gains and losses respectively of +150 and –175 million tonnes (Tubiello and Fischer, 2007; Fischer *et al.*, 2007).

FIGURE 3: CLIMATE CHANGE IMPACTS ON CROP YIELDS, 2000-2080



Projected changes in crop yields in 2080; percent changes with respect to a year 2000 baseline

Sources: Cline, 2007; Tubiello et al., 2008

Thus climate change, despite the possibility of small effects at the global scale, may have particularly serious consequences in developing countries, owing to the predominance of agriculture in their economies, scarcity of capital for adaptation measures, their warmer baseline climates, and their heightened exposure to extreme events and where about one billion people are currently undernourished. In fact, climate change is likely to increase the number of people at risk of hunger compared with reference scenarios with no climate change. Depending on the socio-economic scenario considered, it is estimated that climate change would increase the number of undernourished by between 10 and 150 million people (FAO, 2009a).

The increased frequency, however, of extremes may increase damage in well-established food production regions of the developed world. For instance, the European heat wave of 2003, with temperatures up to 6°C above long-term means and precipitation deficits of up to 300 mm, resulted in crop yields of 30 percent below long-term averages, as well as severe ecosystem economic and human losses. Also, as seen during the food crisis of 2007–2008, shortages in developed countries can affect food security in more vulnerable regions.

By agro-ecological zones

In coming decades, expected changes in temperature and precipitation regimes, and associated soil moisture conditions, will modify the suitability of crop species and cultivars, leading to management changes, such as increased need for irrigation in many regions, new crop calendars and altered planting and harvesting operations. Agroclimatic assessments, reviewed by the IPCC, predict, in general, a northward shift of thermal regimes, reducing significantly boreal and arctic ecosystems (60 percent reduction of current total 2.1 billion ha). In contrast, tropical zones would expand north and south of their current belt. Importantly, models predict significant expansion of arid and semi-arid areas; largely located in developing countries. Currently, world-wide almost one billion people live in arid lands; more than 180 million people in Africa alone. By the 2080s arid and dry semi-arid areas in Africa may increase by 5–8 percent, or 60–90 million ha.

Concerning changes in mean climate conditions alone, at temperate latitudes the areas potentially suitable for cropping will expand, the length of the growing period will increase and crop yields may rise. A moderate incremental warming in some humid and temperate grasslands may increase pasture productivity and reduce the need for housing and for compound feed. These gains have to be set against an increased frequency of extreme events however, for instance heat waves and droughts in the Mediterranean region or increased heavy precipitation events and flooding in temperate regions, including the possibility of increased coastal storms.

In drier areas, climate models predict increased evapotranspiration and lower soil moisture levels. As a result, some cultivated areas may become unsuitable for cropping and some tropical grassland may become increasingly arid. Furthermore, semi-arid and arid pastures are likely to see reduced livestock productivity and increased livestock mortality. A rise in temperature will expand the range of many agricultural pests and increase the ability of pest populations to survive the winter and attack spring crops.

Climate change will not only affect production patterns, but also the ability of individuals to use food effectively by altering the conditions for food safety and by changing the disease pressure from vector, water and food-borne diseases. A main concern related to climate change and food security, which is not quantified in global assessments, is that under new climate regimes, higher incidence of infectious diseases may increase hunger, initiating a vicious circle whereby the malnourished become more susceptible to infectious disease (IPCC, 2007).

Furthermore, increases in daily temperatures may increase the frequency of food poisoning, particularly in temperate regions, while warmer seas may contribute to increased cases of poisoning of humans by shellfish and reef-fish in tropical regions with a poleward expansion of the disease. Extreme rainfall events can increase the risk of outbreaks of waterborne diseases. Likewise, the impacts of flooding will be felt most strongly in environmentally degraded areas and, where basic public infrastructure is lacking. This will raise the number of people exposed to waterborne diseases, e.g. cholera, and thus lower their capacity to effectively use food (Schmidhuber and Tubiello, 2007).

1.4 Expected interactions with bio-energy demand

Bioenergy is renewable energy derived from non-fossil biological sources, supplying heat and electricity for many processes and at several scales. Biofuel derived from agricultural or forested plant material is a bio-energy source, and includes fuelwood, charcoal, bio-ethanol, biodiesel, biogas (methane) or biohydrogen. Currently bio-energy represents about 10 percent of global energy use, mainly for traditional uses (cookstoves, heating, etc.) in developing countries. While considering bio-energy in general, this report focuses in practice on bio-ethanol and biodiesel, currently the main liquid biofuels in transportation, whose projected trends and foreseen economies of scale are thought to have the greatest potential impact on land and water use in coming decades.

Trends in liquid biofuel demand and production

Global liquid biofuel supply reached 0.7 million barrel daily (Mb/d) (34.1 Mtoe) in 2007, an increase of 37 percent for 2006, and equivalent to 1.5 percent of total road transport fuel. Current trends indicate that worldwide demand will rise significantly, to 1.6 Mb/d in 2015 and to 2.7 Mb/d in 2030; meeting 5 percent of total world road-transport energy demand (IEA, 2009). Although these are very significant increases, the International Energy Agency (IEA) suggests that a coordinated global commitment to stabilize the concentration of greenhouse gasses (GHG) at 450 ppm of CO_2 equivalent would require a further doubling of global liquid biofuel demand in 2030, with the increased use of liquid biofuels in the transport sector accounting for 3 percent of CO_2 savings.

Concerns about competition of bio-energy and food over scarce land and water resources, impacts on food security, actual GHG emissions savings, and environmental sustainability of production, have had many countries reassessing their near-term production targets for liquid biofuels. This is particularly true for 'first generation' biofuels, i.e. those obtained from dedicated energy crops such as maize and sugar cane. Potential negative impacts on cropland and food security may be reduced by the introduction of second-generation liquid biofuels, i.e. fuels derived from biomass waste. It is expected that by 2030 one-quarter of biofuel production will be of this origin (IEA, 2009).

Different generations of biofuels and cost effectiveness

First generation liquid biofuels include sugarcane-based ethanol (mainly in Brazil), corn-based ethanol (mainly in the United States) and rapeseed-based biodiesel (mainly in Europe). Devoting land to first generation biofuel crop production can lead to GHG emission reductions as carbon is sequestered by the growth of the feedstock, provided that the cultivation is GHG neutral and does not trigger global indirect land use change offsetting the GHG emission reduction (Searchinger *et al*., 2008).

Second generation liquid biofuels include ligno-cellulosic ethanol and Fischer-Tropsch diesel for road transport with waste and non-land grown algae-based second-generation fuels being especially promising. Nevertheless, despite increasing research efforts, these second generation biofuels are far from being deployed commercially. In the long-term, however, second generation biofuels are expected to be considerable cheaper to produce than their first generation equivalents: costs are expected to decrease from increased production volumes, economies of scale, and increased experience of the production process (IEA, 2009).

Accounting for carbon benefit

Accounting for carbon benefit of biofuels must reflect the GHG emissions from indirect land-use change and land clearance. Clearing forest and grassland would provoke the release of carbon previously sequestered on that land. The GHG negativity, i.e. net mitigation, compared to use of fossil fuel replaced by some of the first-generation liquid biofuels has been shown to be nonexistent. Searchinger *et al*. (2008) reported that corn-based ethanol nearly doubles GHG emissions over a 30-year period and increases greenhouse gases for 167 years, while liquid biofuels from switchgrass, if grown on corn lands in the United States, increase emissions by 50 percent. Suitable feedstocks with lower life-cycle GHG emissions than traditional fossil fuels, and with little competition with food production, were suggested by Tilman et al. (2009) and include: perennial plants grown on abandoned degraded lands no longer used for agriculture; crop residues (such as corn stover and straw from rice and wheat); sustainably harvested wood and forest residues; double crops and mixed cropping systems and municipal and industrial wastes.

Traditional biomass

An IEA estimate indicated that currently approximately 2.5 billion people in developing countries depend on traditional biomass as their main cooking fuel (IEA, 2009). The IEA projected that much of the energy consumed in 2030 in Africa and non-OECD countries is traditional biomass, and waste such as fuelwood, charcoal, dung and crop residues, much of which are not traded commercially. Although being carbon-neutral, these are typically used in inefficient and polluting ways and have led to considerable land degradation.

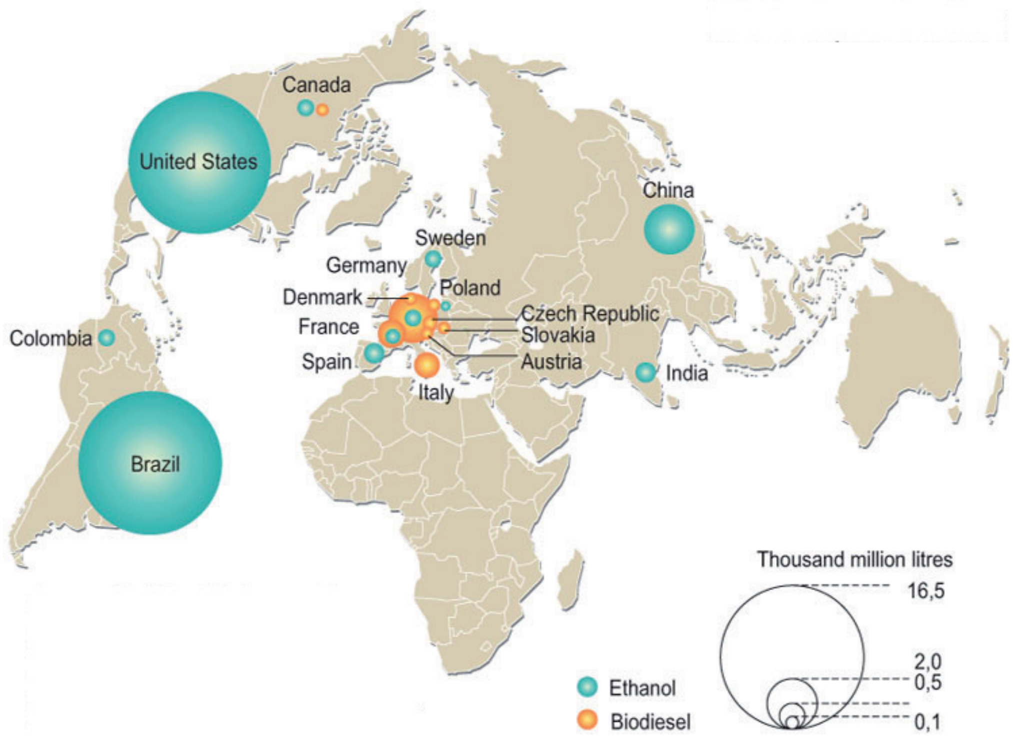
Projected land and water use

Food production may increasingly have to compete with bio-energy for scarce land and water resources in the coming decades. Studies addressing the possible consequences for world food supply have only started to surface, providing both positive and negative views. For instance, Searchinger *et al*. (2008) calculated that United States ethanol production of 55 billion liters, expected by 2015, would divert maize from about 13 million ha of cropland in the United States, causing another 11 million ha of land to be placed under cultivation elsewhere in the world; including 2.8 million ha in Brazil, 2.3 million ha in China and India and 2.2 million ha in the United States. About 3 billion ha might be converted worldwide to produce grain displaced by increased biofuel demand.

Certainly, bio-energy programmes that result in competition for the land and water resources necessary for the resilience of ecosystems and livelihoods should be minimized. Great concern has been expressed for the overall sustainability of first generation biofuels. Direct and indirect land-use change can lead to additional environmental pressures on land and water resources, habitat destruction and loss of biodiversity and thus contribute to further food insecurity through the competition for land and resulting increases in food prices (van der Velde *et al*., 2009; Tilman *et al*., 2009). (Figure 4).

Currently, global irrigation water used for biofuel production, mainly for sugar cane and maize, is estimated at 1–2 percent of world total irrigation water use (UN, 2009). Regionally, while it is still negligible in Brazil and the European Union as a share of total use, it is 2 percent in China and 3 percent in the United States. Hoogeveen *et al*. (2009) projected increases of irrigation water use for biofuels by 74 percent in 2017 compared to 2008, if agricultural practices remained the same. The United Nations (2009) estimates that implementing all current national biofuel policies and plans worldwide would take 30 million ha of cropland, requiring 5–10 percent of current irrigation water. In fact, irrigation water demand for biofuels may be limited in the future by increased adoption of rainfed biofuel crop species.

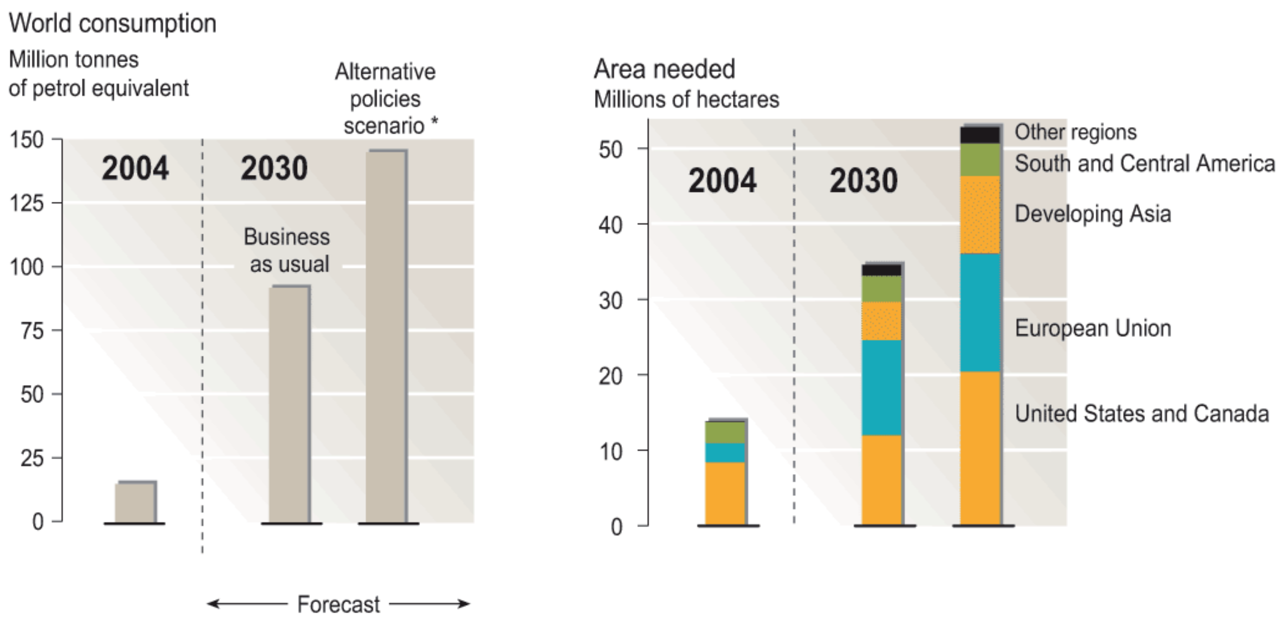
FIGURE 4A: PRODUCTION OF LIQUID BIOFUEL



Regional distribution of current liquid biofuel production
(Available at: http://www.unep.org/publications/ebooks/kick-the-habit/ShowPicture.aspx?imgID=ID0EIJBG).

Sources: Earth Trends Enviromental Information Portal World Resources Institute 2007 (using Worldwatch 2006; US Department of Energy, 2006); REN21, Renewables 2006 global status report, Worldwatch Institute; F.O. Licht world ethanol & biofuels report 2005

FIGURE 4B: TWO SCENARIOS FOR BIOFUELS BY 2030



Current and projected liquid biofuel production and associated land area needed.
(Available at:http://www.unep.org/publications/ebooks/kick-the-habit/ShowPicture.aspx?imgID=ID0EHKBG).

Sources: Cline (2007)

Considering that it takes on average 2 500 litres of water (about 820 liters of it irrigation water) to produce 1 liter of liquid biofuel, the same amount needed to produce food for one person for one day (UN, 2009), local water scarcity problems related to irrigation of bio-ethanol crops are in any case a serious concern; and exist today. They will likely continue to worsen during this decade, especially in countries with fast-developing economies such as India, China, Thailand and South Africa, where growing demand for food and energy is increasing pressure on already scarce water resources (Hoogeveen *et al*., 2009).

2. Technical response option

2.1 Land and water management options for adaptation

Crop and soil management

An essential feature of agriculture is the ability to adapt to natural variability to ensure long-term sustainability of food production. To this end, a large number of existing farm-level management practices are already available as a basis for devising climate change response strategies needed in coming decades. These include growing new varieties and species that are more adapted to altered thermal and hydrological conditions; rescheduling of farm management practices such as irrigation and nutrient application to better match altered phenological cycles; implementation of technologies that conserve water and soil, etc.

Despite the existence of a considerable 'bag of tricks' already available to farmers today, successful implementation of adaptation responses in coming decades requires key additional challenges: i) from the farmer's side, and somewhat autonomously, the ability to implement new or previously known technologies in real time, i.e. as the climate changes; ii) from the policy-maker's side, in a planned and forward-looking fashion, the ability to enable farmers to make changes when needed, through development of economic incentives and delivery of necessary infrastructure; and iii) from the public and private sectors' side, the ability to put in place observing and monitoring systems capable of informing and supporting decision-making for both autonomous and planned adaptation (Tubiello and Rosenzweig, 2008).

Autonomous adaptation actions are defined as responses that will be implemented by individual farmers, rural communities and farmers' organizations, depending on perceived or real climate change in the coming decades, and without intervention or coordination by regional and national governments and international agreements. To this end, maladaptation, e.g. pressure to cultivate marginal land, or to adopt unsustainable cultivation practices as yields fall, may increase land degradation and endanger the biodiversity of both wild and domestic species, possibly jeopardizing future ability to respond to increasing climate risk later in the century. Planned adaptation, therefore, including changes in policies, institutions and dedicated infrastructure, will be needed to facilitate and maximize the long-term benefits of adaptation responses to climate change.

Several simulation studies suggest the possibility of relative benefits of adaptation with low-to-moderate warming, although several response strategies may place extra stress on water and other environmental resources as warming increases. In general, increasing the resilience of agricultural systems requires better reconciliation of biodiversity and agricultural production needs (Butler *et al*., 2007). From the technical perspective of needed solutions, many management-level adaptation options are largely extensions or intensifications of existing climate risk management, or of known production enhancement activities, developed over past decades in response to climate variability across a range of plant-growth environments. Ways to alter management of production systems to deal with projected climatic changes include:

- altering inputs, varieties and species for increased resistance to heat shock and drought, flooding and salinization;
- altering fertilizer rates to maintain grain or fruit quality;
- altering amounts and timing of irrigation;
- altering the timing or location of cropping activities;
- diversifying towards rotation systems, including adding cover crops and shelter belts for improved soil–water retention and reduced erosion;
- making wider use of integrated pest and pathogen management, developing and using varieties and species resistant to pests and diseases; improving quarantine capabilities and monitoring programmes;
- increasing use of climate forecasting to reduce production risk;
- matching livestock stocking rates and grazing to pasture production, altered pasture rotation, alteration of forage and animal species/breeds, reassessing fertilizer use and supplementary feeds and concentrates;
- changing forest management, including hardwood or softwood species mix, timber growth and rotation periods; shifting to more productive areas under new climate conditions, adjusting fire and pest control management systems;
- introducing forest conservation, agroforestry and forest-based activities for diversification of rural incomes;
- altering fisheries catch size and effort; improving the environment where breeding occurs; reduce fishing rates to sustain yields of fish stocks; and
- developing integrated food-energy systems (IFES—see section 2.2).

Broadly speaking, adapting to changes in the mean climate will require farmers to: i) adapt management; ii) choose other more robust crop varieties; iii) select other crops; and iv) modify water-management practices. Such changes will come as a result of scientific knowledge and field experience. If widely adopted, these adaptations singly, or in combination, have the potential to offset negative climate change impacts and take advantage of the positive. It has been stressed that most farm-level adaptation responses may counterbalance impacts at low-to-medium temperature increases, allowing for coping with up to 1–2 °C local temperature increases, an effect that can be seen as ‘buying time’ (Howden *et al*., 2007). Adapting to increased frequency of extreme events, on the other hand, will be much harder, especially since such new regimes may not have historical analogues.

Benefits of adaptation will vary with the type of crop and with changes in temperature and rainfall (IPCC, 2007). For wheat, the potential benefits of management adaptations are similar in temperate and tropical systems (17.9 percent versus 18.6 percent). The benefits for rice and maize are smaller than those for wheat, with a 10 percent yield benefit when compared with yields when no adaptation is used. The benefits of adaptation for rice, wheat and maize crops translate to damage avoidance of up to 1–2 ^{o}C in temperate regions and up to 1.5–3 ^{o}C in tropical regions. Another way of viewing the benefits of adaptation is that damage avoidance of 1–3 ^{o}C translates to potentially delaying negative impacts by up to several decades, providing valuable time for mitigation efforts and adaptation planning.

Several significant caveats need to be applied on the above positive results on impacts and adaptation. Changes in pest and disease incidence, increased air pollution, the actual strength of CO_2 responses in real field situations, increased climate variability and the frequency of extremes may lessen farmers' ability to adapt. Furthermore, capacity to implement needed adaptations may not be available, particularly in developing regions where subsistence agriculture is predominant. On the other hand, inclusion of a broader range of adaptations including more significant and systemic change in resource allocations would presumably increase the benefits, particularly if those adaptations included alternative land-use and alternative livelihood options.

Genetically modified crops

The contribution genetically modified crops can make in adaptation to climate change is controversial. Nevertheless, recent examples such as the identification of the gene responsible for rapid stem elongation in deepwater rice ('snorkel rice', Hattori *et al*., 2009) may contribute to rice breeding in lowland areas and ultimately lead to reducing the devastation of rice crops caused by monsoon flooding in Asia and boost rice production in flood-prone areas.

Water management

Water management is a critical component of adaptation to both climate and socio-economic pressures in coming decades. These pressures will be driven by changes in water availability, in water demand for agriculture and other competing sectors. Practices that increase the productivity of irrigation water use – defined as crop output per unit of water use – may provide significant adaptation potential for all land production systems under future climate change. At the same time, improvements in irrigation performance and water management are critical to ensure the availability of water both for food production and for competing human and environmental needs (FAO, 2007; FAO, in press). A number of farm, irrigation system and basin level adaptation techniques and approaches are specific to water management for agriculture. They include:

- adoption of varieties or species with increased resistance to heat shock and drought;
- modification of irrigation techniques, including amount, timing or technology;
- adoption of supplementary irrigation in rainfed cropping;
- adoption of water-efficient technologies to 'harvest' water and conserve soil moisture (e.g. retention of crop residue, mulching, etc.);
- improved water management to prevent waterlogging, erosion and leaching;
- modification of crop calendars, i.e. timing or location of cropping activities;

- implementation of seasonal climate forecasting;
- adaptation of water allocation rules that reward high return on water;
- conjunctive use of surface water and groundwater; and
- adoption of structural and nonstructural measures to cope with floods and droughts.

Additional adaptation strategies may involve land-use changes that take advantage of modified agroclimatic conditions. A few simulation studies show the importance of irrigation water as an adaptation technique to reduce the impact of climate change. In general, however, projections suggest that the greatest relative benefit of adaptation is to be gained under conditions of low-to-moderate warming. Indeed, adaptation practices that involve increased irrigation water use will likely place additional stress on water and environmental resources as warming and evaporative demand increase (IPCC, 2007).

Changing irrigation practices may mitigate part of the impact of drought on crop yield, or even be useful in combating heat stress. For instance, during the 2003 heat wave and during hot summer days in Europe, farmers irrigated at midday simply to reduce canopy temperature and thus to minimize plant heat stress.

Planned adaptation solutions should focus on developing new infrastructure, policies and institutions, including addressing climate change in development programmes; increasing investment in irrigation infrastructure and precision water-use technologies; ensuring appropriate transport and storage infrastructure; revising land tenure arrangements (including attention to well-defined property rights); and establishing accessible, efficiently functioning markets for products and inputs (including water pricing schemes) and for financial services (including insurance).

Policies that aim to reward improvements in irrigation, either through market mechanisms or increased regulations and improved governance, are an important tool for enhancing adaptation capacity at a regional scale. However, unintended consequences may be increased consumptive water use upstream, resulting in downstream users being deprived of water that would otherwise have re-entered the stream as return flow (IPCC, 2008).

Besides techniques already available to farmers and land managers today, new technical options need to be made available through dedicated research and development efforts, to be planned and implemented now, to augment overall capacity to respond to climate change in future decades. Technological options for enhanced R&D include traditional breeding and biotechnology for improved resistance to climate stresses such as drought and flooding in crop, forage, livestock, forest and fisheries species.

2.2 Land and water management options for mitigation

Adaptation in agriculture and forestry should be concurrent with mitigation: reducing greenhouse gas emissions and increasing carbon sequestration through sustainable agricultural and forestry practices including conservation of soil and ecosystems. Agriculture, and associated deforestation activities, is responsible for one-third of total anthropogenic greenhouse gas emissions, or about 13–15 billion tonnes CO_2 per year. It emits about 25 percent of total carbon dioxide (largely from deforestation), 50 percent of methane (rice, enteric fermentation, animal waste), and 75 percent of N2O (fertilizer application, animal waste) emitted annually by anthropogenic activities.

A number of mitigation strategies in the agriculture and forestry sectors have been identified as useful in achieving the goal of stabilization of atmospheric concentrations between 450–550 ppm CO_2, for which global GHG reductions should total 15–25 billion tonnes/CO_2e/yr-1 by 2030 (Table 2). In the forestry sector, mitigation strategies include reduced deforestation and degradation of tropical forests (REDD+), sustainable forest management (SFM) and forest restoration (FR), including afforestation and reforestation (A/R). In agriculture, they involve reduction of non-CO_2 gases through improved crop and livestock management and agroforestry practices, enhanced soil carbon sequestration in agricultural soils through reduced tillage and land restoration, and production of bio-energy from biomass.

Table 2 indicates that the mitigation potential achievable by a complex mix of actions in both the agriculture and forestry sector is significant compared to the global GHG reductions needed in 2030. Importantly, the total potentially achievable land-based mitigation is quite close to total emissions of the agriculture sector as a whole. If achieved, they would contribute to making this sector nearly carbon-neutral.

TABLE 1: **ANNUAL ANTHROPOGENIC GREENHOUSE GAS EMISSIONS**

	2005	
	Billion tCO2e	Percentage share
Global	**50**	
Agriculture	5-6	10-12
Methane	(3.3)	
N2O	(2.8)	
Forestry	8-10	15-20
Deforestation	(5-6)	
Decay and peat	(3-4)	
Total agriculture and forestry	**13-15**	**25-32**

Source: FAO, 2008.

TABLE 2: **MITIGATION POTENTIAL IN AGRICULTURE AND FORESTRY IN 2030**

	2030 Reductions
	Billion tCO2e
Global	**15-25**
Agriculture	1.5-5.0
Reduction of non CO2 gases	(0.3-1.5)
Agroforestry	(0.5-2)
Enhanced soil carbon sequestration	(0.5-1.5)
Forest	2.5-12
REDD+	(1-4)
SFM	(1-5)
FR including A/R	(0.5-3)
Bio-energy	0.1-1.0
TOTAL	**4-18**

Source: FAO, 2008.

Enhancing carbon sinks (reduced tillage, afforestation, etc.)

Conservation practices, no-till farming, implementation of cover crops and agroforestry are likely to both improve adaptive capacity through increasing the resilience of the agricultural system, as well increasing carbon storage in agricultural soil. Increasing the organic matter and soil carbon content of degraded cropland would also increase crop yields (Lal, 2004).

Of the roughly 150 billion tonnes of carbon that were lost in the last century because of land conversion to agriculture and subsequent production, about two-thirds were as a result of deforestation and one-third, roughly 50 GTC, was lost owing to reduction of soil organic matter from cultivation practices and exports in food products. The latter figure therefore represents the maximum theoretical amount of carbon that could be restored in agricultural soils. In practice, as long as 40–50 percent of total aboveground production is exported as food or other agricultural product, the actual carbon that can be restored in agricultural soils is much lower, perhaps no more than 20 percent (Rosenzweig and Tubiello, 2007).

Efforts to improve soil quality and raise carbon levels can be grouped into two sets of practices: crop management and conservation tillage. Both practices evolved as means to enhance sustainability and resilience of agricultural systems, rather than with carbon-sequestration in mind. They include 'best practice' agricultural techniques, such as use of cover crops and/or nitrogen fixers in rotation cycles; judicious use of fertilizers and organic amendments; soil water management improvements to irrigation and drainage; and improved varieties with high biomass production.

Table 2 shows that, over the next 20 years, best practice and conservation tillage alone could store up to 1.5 billion tonnes CO_2 annually in agricultural soils. Larger amounts can be sequestered via agroforestry practices, especially if established on marginal lands, or through cropland conversion and conservation programmes. An important caveat to the implementation of best practice and reduced tillage agriculture as a means to enhance carbon sequestration is that CO_2 emitted from the manufacture and use of additional agricultural inputs may negate all or part of the increased carbon sequestered in soils (Schlesinger, 1999).

Agriculture may help to mitigate anthropogenic greenhouse emissions through the production of biofuels. If available marginal land were used for energy crops, the IPCC projects significant reduction of GHG through displacement of fossil fuels by biofuels — globally up to 1.5 billion tonnes CO_2 annually by 2030. It has, however, been shown that factors such as input availability, especially water and fertilizer, and indirect land-use changes may increase the energy and carbon costs of producing liquid biofuels to inefficient levels; in addition competition of bio-energy with food over scarce land and water resources are problematic.

These questions need to be addressed before large-scale bio-energy efforts are implemented further. Specifically, while current knowledge allows for some positive action, better understanding and more information is needed to develop better regulations, guide investments and protect ecosystems and communities locally, nationally and internationally, i.e. across the entire spectrum of the bio-energy-land use and production chain.

Reducing GHG emissions (especially with respect to methane and Nitrous oxide (N2O) paddy, livestock)

Methane and N2O represent the bulk of agricultural emissions, and therefore mitigation of these non–CO_2 greenhouse gases is very important. In addition, the fact that both gases have a high global warming potential (GWP)[2] makes their reduction quite effective from a climatic perspective, as well as attractive in a carbon market regime, i.e. given the higher GWP involved, 1 tonne reduction of CH4 or N2O commands several times the price of a 1 tonne reduction of CO_2.

Mitigation options for capturing methane include: development of more efficient rice cultivation systems, including lower requirements for water use or shifts from transplanted rice to direct-seeded rice systems or alternate wet-dry production system; changes in livestock production systems with different stocking rates, nutrition patterns, etc; recovery of biogas in animal waste management systems and from organic waste, with flaring for energy use (FAO, 2006b).

In intensive agricultural systems with crops and livestock production, N2O emissions typically dominate, often contributing more than half, 60 percent of total greenhouse gas emissions from farms. The N2O contribution arises from substantial N emissions from fertilized fields and animal waste. Strategies for effective mitigation of N2O emissions are far more difficult than those focusing on CO_2 and methane, given the largely heterogeneous nature of emissions in space and time and thus the difficulty of timing fertilizer applications and/or manure management. Uncertainties in emission factors also complicate the assessment of efficient N2O-reduction strategies.

Current techniques focus on reduction of absolute amounts of N-fertilizer applied to fields, as well as for livestock feeding regimes that reduce animal excreta. An effective strategy for mitigating non-CO_2 gases in intensive mixed crop-livestock farming systems, such as those in Europe and North America, might be a change in human diet towards less meat consumption, thus reducing livestock numbers, as well as grain production for feed (Rosenzweig and Tubiello, 2007).

Other options: integrated food energy systems and Biochar

The concept of Integrated Food Energy Systems (IFES) indicates a farming system model designed to integrate, intensify, and thus increase the simultaneous production of food and energy in two ways:

- by combining energy and food crops on the same plot (e.g. intercropping or agroforestry systems); and

- through closed loop/'zero waste' systems where the by-product of one type of product is used to produce the other (e.g. bagasse for energy as a by-product of sugar production, animal feed as a by-product of corn-ethanol production).

Such systems may lead to GHG mitigation through efficient production of food and bio-energy on farms. They do not, however, entirely solve the problem of competition for land or water: in conditions of scarcity, there will always be competition for biomass production that such systems can only address to a certain extent. In particular, the competition for organic matter from crop residues between energy and soil management will always be acute in semi-arid environments.

Recently biochar, which is pyrolyzed biomass (charcoal) has been proposed as a mitigation option to improve soil conditions. When applied to soil it sequesters carbon and improves soil conditions (Lehmann, 2007). However, a number of questions related to the sustainable application of biochar do remain. There are many gaps in current knowledge associated with biochar properties, the long-term effects of biochar application on soil functions and threats, and its behaviour and fate in different soil types (e.g. disintegration,

[2] GWP defines the global warming potential of a given GHG compared to CO2, on a tonne per tonne basis. For instance, GWP of CH4 is 21; GWP of N2O is 310.

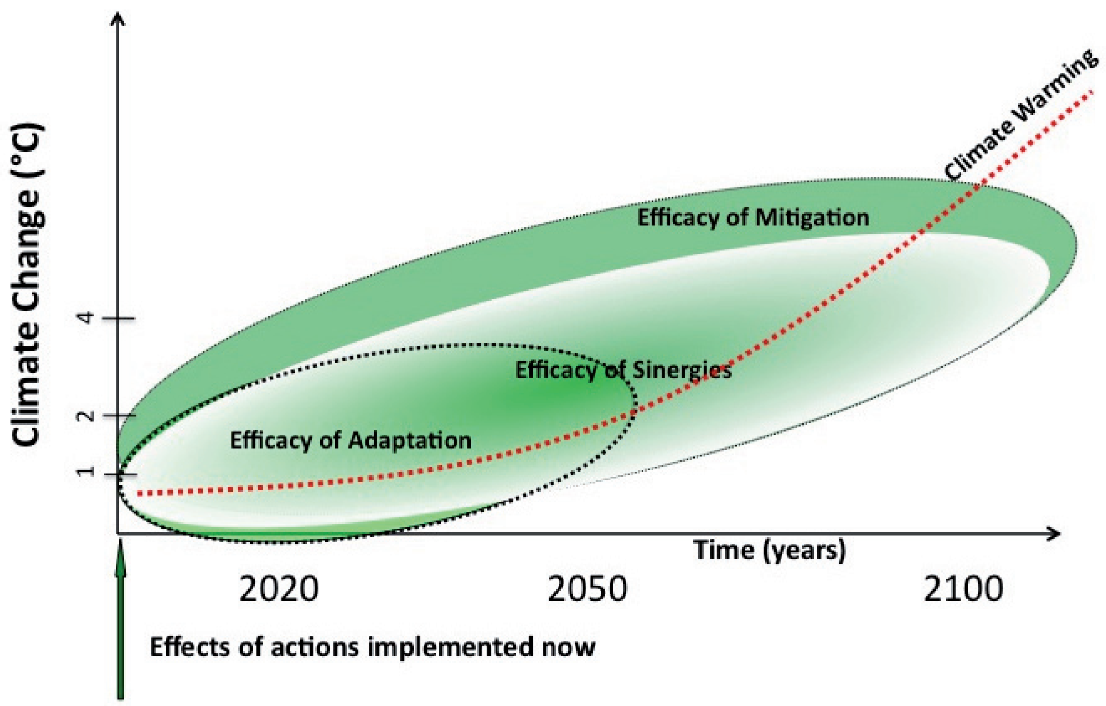
mobility, recalcitrance, interaction with soil organic matter), as well as sensitivity to management practices, which all require further scientific research.

Small-scale biochar systems that lead to a reduction of net GHG emissions have been suggested as part of carbon offset mechanisms and may contribute to soil carbon storage in Africa (Whitman and Lehmann, 2009). However, given the extensive burning of biomass for energy in Africa, one of the problems may relate to the willingness of farmers to forego an energy source (biochar) once it has been created. The use of biochar requires transparent certification and monitoring schemes if it is to be used in carbon credit trading schemes.

2.3 Synergies and offsets between adaptation and mitigation

Because climate changes and socio-economic pressures together will shape future demands for food, fibre, and energy, synergies need to be identified between adaptation and mitigation strategies, so that robust options that meet both climate and societal challenges in the coming decades can be developed (FAO, 2009c, d). Ultimately farmers, and others in the agricultural sector, will be faced with the dual task of contributing to global reductions of carbon dioxide and other greenhouse gas emissions, while having to cope with an already changing climate (Figure 5).

FIGURE 5: ADAPTATION AND MITIGATION ROLES FOR LAND AND WATER RESOURCES



The efficacy of adaptation and mitigation actions implemented today can be thought of as a qualitative measure of their ability to reduce climate damage as a function of climate warming. In general, adaptation actions work well to limit damage from low-to -medium warming (i.e. from now until mid-century), while mitigation actions work on longer timescales, with benefits materializing only in the second half of this century. Joint adaptation and mitigation actions that can be implemented today across a wide range of land and water resource management solutions can provide both adaptation benefits in the short term and long-lasting mitigation benefits in the longer term.

First, one should consider interactions between adaptation strategies, which will certainly be progressively implemented by farmers as the climate changes, and the mitigation potential of the adapted system. In general, wherever farmers try to 'fix' the system to compensate for climate change, while keeping their production model rather than adapting, this will likely translate into more energy intensive agriculture, and therefore not good for the climate. For example, poleward shifts in agricultural zones may lead to increased cultivation of those previously marginal and currently undisturbed areas – certainly seen as a boon in certain countries — resulting in substantial losses of carbon above and below ground.

The same might be true under major shifts in rotation systems with very different production levels, occurring across regions over large areas, as well as for land that will become too arid and will have to shift to irrigation. For livestock production in intensive systems, warmer conditions might trigger the implementation of enhanced cooling and ventilation systems. The former strategy would clearly counter on-farm mitigation efforts owing to the associated increased energy use.

On the contrary, several adaptation activities leading to increased systems resilience and improved rural incentives may be attractive to carbon markets because of their associated mitigation value. No-regrets, win-win strategies that provide additional opportunities to poor rural communities may, for instance, include forestry management and agroforestry techniques; agricultural 'good practices' that conserve soil and water resource; and properly scaled bio-energy projects for rural communities.

Most of the adaptation practices described in the previous sections will positively reinforce mitigation potential. Use of rotations, more judicious use of fertilizers, increased farm diversity, improved grazing activities lead to production systems that are less vulnerable to the impact of climate change, but also to increased organic matter in the soil and thus sequestration of carbon in the soil. In livestock management, a reduction in stocking densities needed to cope with heat stress would positively contribute to mitigation of non-CO_2 greenhouse gases. Improved irrigation and fertilization systems in marginal regions can lead to more vigorous crops and overall vegetative cover, thus greatly enhancing soil carbon storage.

A new climate regime may alter the effectiveness of proposed adaptation and mitigation strategies as compared to their known effects under current conditions. For instance, elevated CO_2 alone will strengthen above and below ground biomass production in agro-ecosystems as well as improve plant water relations; with positive effects on both resilience and carbon storage. Likewise, longer growing seasons may allow for increased vegetative growth and thus carbon inputs into soils. Warmer temperatures may have negative effects as well, for instance by increasing decomposition rates of soil organic matter, with increased release of soil carbon into the atmosphere. Increased variability and higher frequency of extreme events may reduce soil carbon storage potential, both by decreasing mean production levels and thus reducing soil organic inputs, as well as by worsening soil quality in the areas affected.

The implications of interactions between mitigation strategies and adaptation need to be considered carefully. For example, enhanced soil carbon sequestration through conversion of marginal lands to forestry, agroforestry, or bio-energy crops, may lead to competition for land and water resources with unintended consequences for food production and markets, so that these strategies would need to be thoroughly evaluated before implementation, considering a range of socio-economic projections.

Importantly, on current agricultural and forestland many mitigation and adaptation solutions are mutually re-enforcing, especially in view of increased climate variability under climate change. This is because most mitigation techniques currently considered in agriculture, including reduced tillage, were originally designed as 'best practice' management strategies, aimed at enhancing the long-term stability and resilience of cropping systems in the face of climate variability or of increased cultivation intensity.

By increasing the ability of soils to hold soil moisture and to better withstand erosion, and by enriching ecosystem biodiversity through the establishment of diversified cropping systems, many mitigation techniques implemented locally for soil carbon sequestration will help cropping systems to better withstand droughts or floods, both of which are projected to increase in frequency and severity in future warmer climates. Similarly, avoiding deforestation and improving techniques for forest conservation and management lead to more resilient and healthy ecosystems, and, if well-coordinated at national levels, sustainable and long-term income opportunities for local communities.

3. Policy and finance response options

3.1 Current global climate agreements and implications for agriculture

The importance of mitigation and adaptation in agriculture, forestry and other land uses is well recognized and is supported by the recent Cancun Agreements of the Conference of the Parties/Meeting of the Parties[3] (COP/MOP) 16. These formalize fundamental issues on renewed efforts for adaptation and mitigation, including Reduced Emissions from Deforestation and Forest Degradation (REDD+), which had begun with the Copenhagen Accords of CP.15/CMP.5

Both the scientific community and international negotiators understand that a large mitigation potential is achievable in managed and natural terrestrial ecosystems. What is also well known is that adaptation activities in agriculture and forestry very often coincide with mitigation solutions, leading to more resilient land production systems for food and fiber while sequestering carbon.

The implication of the Cancun Agreements for agriculture and forestry-based projects is significant. These include substantial financial support for developing countries i.e. a commitment to make available US$30 billion during 2010–2012, increasing to US$100 billion per year by 2020, in order to implement adaptation and mitigation actions, including reduced forest deforestation and degradation activities (REDD+), both representing pillars of land-based climate response strategies for rural development (FAO, 2008). In particular, decisions formalized in Cancun add as key activities in REDD+ forest conservation, sustainable forest management, and enhancement of carbon sinks.

At the same time, the non–permanent nature of carbon stored in ecosystems, coupled with difficulties in estimating and then monitoring emission reductions in agriculture and forestry, have lead to severe limitations in the use of land-based carbon offsets, limiting their use especially in regulated markets, such as the European Union Emission Trading System (EU-ETS). Several efforts within the Ad-Hoc Working Groups at UNFCCC focus on how to best take advantage of the many synergies that exist between mitigation and adaptation in agriculture and forestry, devising rules for project design, monitoring and verification that are simple enough to be widely adopted.

[3] Parties to the Kyoto Protocol

With current mechanisms, the Kyoto Protocol (KP) of the UNFCCC is the only legally binding international climate policy agreement. It establishes a cap and trade system among developed countries among its parties (Annex I), for the period 2008–2012, with a global annual emission cap set at 5 percent below 1990 GHG emissions. Under the KP, market-based mechanisms can be used towards emission reductions that also facilitate technology transfers and promotion of sustainable development in developing non-Annex I parties to the KP. These are emission trading –the EU-ETS being the largest – and project-based flexible mechanisms, such as the Certified Emission Reductions (CERs) of the Clean Development Mechanisms (CDM), and the Emission Reduction Units (ERU) of the Joint Implementation (JI)[4].

Another important UNFCCC financial mechanism is linked to the funding available through the Global Environmental Facility (GEF) Trust Fund. This funding is available for both mitigation and adaptation projects.

3.2 Carbon financial mechanisms for agriculture and forestry

Both CDM and JI mechanisms make provisions for the inclusion of agriculture and land use, land-use change and forestry (LULUCF) activities. While CERs can only be produced from afforestation and reforestation (A/R) activities, ERUs can be also generated in projects involving forest and cropland management, grazing land management and re-vegetation.

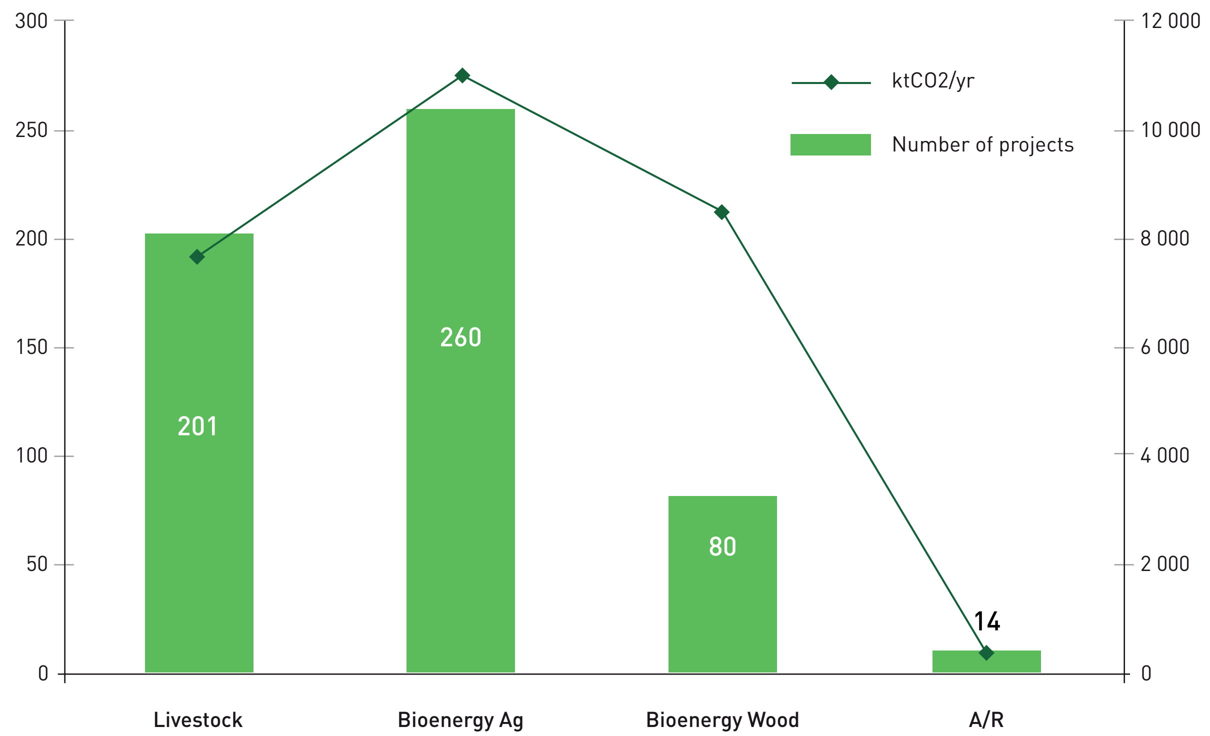
Currently there are over 3 000 registered CDM projects, which generate about 400 million tCO_2e annually. This corresponds to US$4 billion per year for the period 2008–2012, at carbon prices of US$10/$tCO_2$. Financial flows related to the JI, the GEF trust funds and Adaptation Fund are an order of magnitude lower. About one-third of currently registered CDM projects are undertaken in agriculture and forestry sectors, generating about 10 percent of the total CER primary market. Thus CDM-related financial flows to developing country agriculture and forestry are expected to be about US$400 million per year for the period 2008–2012 (Tubiello *et al*., 2009).

The majority of these projects are in the agricultural sector, generating about two-thirds of the 'land based' credits, and focus on two activities: methane capture within improved animal manure management systems and bio-energy production from agricultural biomass waste. By contrast, a mere 25 percent of land-based CDMs are related to the forestry sector and focus on renewable energy from woody biomass (Figure 6). Although only 15 CDM A/R projects have been registered to date, an impressive acceleration in trends is underway, as 14 out of these 15 projects have been registered over the 2009–2010 period. The other A/R project was registered in 2006.

Finally, the geographic distribution of CDM projects in agriculture and forestry is severely skewed towards few regions and countries. Latin America and Asia combined account for over 95 percent of total CERs generated in land-based sectors. Three countries alone, i.e. Brazil, Mexico and India, generate over 60 percent of this total. By contrast, Africa and the Middle East are significantly underrepresented regions. For instance, of the roughly US$400 million/year in land-based CDM flows, only about US$5 million reach sub-Saharan Africa.

[4] CDM projects are implemented in developing countries (non-Annex I), while JI projects are largely implemented in economies in transition. Emission trading systems such as those implemented under the KP, for instance the EU-ETS, are based on specific GHG emission caps, and represent so-called cap and trade systems. The carbon markets established in association with these systems are referred to as 'regulatory markets', since the underlying emission caps are defined by law and thus enforceable.

FIGURE 6: DISTRIBUTION OF CDM PROJECTS IN AGRICULTURE AND FORESTRY BY TYPE AND BY GENERATED EMISSION REDUCTIONS



Source: UNFCCC data, March 2010

3.3 Adaptation funds

The fact that adaptation to the adverse effects of climate change is vital to reducing the impacts of climate change occurring now and to increasing resilience to future impacts is now well understood and agreed in international fora. Adaptation funding and implementation is also an issue of equity between developed and developing countries, given that the bulk of the climate change problem was created by the former group, while it is largely poor countries in the second group that will be most vulnerable.

Issues being addressed by Parties under the various Convention bodies, include: enhanced action on adaptation as part of the Bali Action Plan under the UNFCCC Ad-hoc Working Group on Long-Term Cooperative Action (AWG-LCA); Nairobi work programme on impacts, vulnerability and adaptation to climate change; development and transfer of technologies, research and observation under the Subsidiary Body for Scientific and Technological Advice (SBSTA); National Adaptation Programmes of Action (NAPAs); and supporting adaptation through finance, technology and capacity-building under the Subsidiary Body for Implementation (SBI).

These are all important programmes. Their challenge revolves around practical implementation of adaptation projects that are real, useful, and consistent with specific country priorities. There is therefore a keen need to move beyond the current necessary phase, euphemistically indicated by most actors in the field as 'learning by doing'.

Funds available for adaptation under the GEF Trust Fund include the Piloting and Operational Approach for Adaptation (SPA), the Special Climate Change Fund (SCCF), and the least Developed Countries Fund (LDCF). A special Adaptation Fund has been set up by UNFCCC, receiving funding directly from the sale of 2 percent of CDM carbon credits. Importantly, the 'Green Climate Fund', discussed at COP/MOP 15 in Copenhagen and formalized in Cancun, is intended as a fundamental, additional UNFCCC financing mechanism, with pledges to disburse about half of its US$30 billion in the period 2010–2012 towards implementation of adaptation projects, increasing to US$100 billion annually by 2020. Enhanced funding for adaptation is to be regulated within the Cancun Adaptation Framework, with strong GCF support.

3.4 Opportunities arising from current and future climate agreements and mechanisms

Many obstacles currently reduce access to CDM funding in agriculture and forestry. This is however an opportunity for new developments in both the current and future climate agreements for a post-2012 regime, as well as a chance to provide guidance to new regulatory schemes under development in many regions of the world (e.g. western and northeast United States; Japan; New Zealand; Australia; South Korea). Key issues can be divided into broad categories: administrative and technical bottlenecks linked to poor capacity in the host country; perceived investor risk in countries with poor infrastructure, services and unclear land tenure; insufficient sector coverage, including monitoring and reporting rules. Much has been written about the first two issues (FAO, 2008). With respect to the third issue, it is well recognized that many more agricultural and forestry activities could be included in the CDM under both its current rules and under expanded rules in a post-2012 regime. For example, reduced enteric fermentation; more precise agrochemical inputs and machinery use; increased irrigation efficiency and productivity; improved agronomic management; agroforestry. By contrast, soil carbon sequestration in agricultural soils, and especially reduced emissions from deforestation and forest degradation (REDD), can have significant carbon sequestration potential, but are not allowed under the current phase of the KP, with the exception of A/R projects.

Another important obstacle, but also an opportunity, is represented by the small-scale and highly fragmented nature of many projects over large areas. Because transaction costs of carbon projects can be high, aggregation of many players and regions is required to generate emission reductions that are large enough to ensure project viability and attractiveness to compliance buyers. The opportunity is offered by the new 'programmatic CDM' tool, discussed below, which may at last facilitate and in fact capitalize on such aggregation needs.

Additional resources, perhaps taking advantage of the recent mandate at COP/MOP 15, should be directed towards developing new methodologies and implementing project activities that extend the scope of land-based emission reductions.

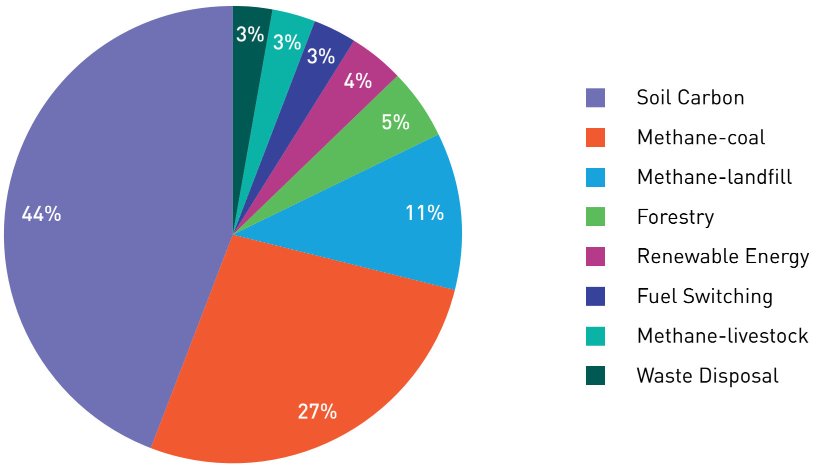
Voluntary markets

Voluntary markets allow for the creation and exchange of carbon offsets generated outside regulatory agreements such as the Kyoto Protocol. Therefore voluntary emission reduction (VERs), also representing 1 tonne of CO_2 equivalent (t/CO_2e), have no compliance value within a cap-and-trade system, and are largely used by companies and individuals to voluntarily reduce GHG emissions[5]. Compared to the UNFCCC regula-

[5] While regulated markets and associated credits such as CERs and ERUs are backed by rules and laws established under the UNFCCC, VERs are typically established by independent third party organizations. However increasingly many VER types follow standards that are compatible with UNFCCC rules–and may soon be accepted within a number of regulated markets, especially in the United States, Australia and Japan.

tory markets, voluntary markets offer large opportunities for agriculture and forestry-based credits and are a significant generator of land-based offsets (Figure 7). They are expected to play a significant role in the post–2012 trading regime, especially since several regional cap and trade schemes consider using significant amounts of voluntary offsets for their compliance. Some voluntary standards already support REDD.

FIGURE 7: VOLUNTARY CARBON OFFSET ACTIVITIES BY SHARE



Source: Chicago Climate Exchange 2010.

In general, voluntary markets are particularly appropriate to small offset projects, often providing greater opportunities compared to the CDM to contribute to sustainable development of small rural communities. The large share of small-scale projects generating VERs is often related to the possibility to make up-front payments to project owners to cover start-up costs, as well as lower entry barriers by applying simpler methodologies and monitoring requirements.

3.5 Possible future developments

According to recent assessments (UNFCCC, 2007, FAO 2008), and as asserted clearly at the COP/MOP 16 in Cancun, developing countries will need about US$100 billion per year to adjust to climate change and minimize risk. Some of these financial flows could come from scaling up land-based carbon projects. Without such scaling up, the future income from current CDM activities in agriculture and the LULUCF sectors would only be about US$1–1.5 billion/yr by 2030, and perhaps reach US$10–15 billion annually in the case of a post-Kyoto regime that included the United States. An additional US$1–5 billion/yr could come from dedicated adaptation funds, as discussed in Copenhagen and Cancun.

There is therefore a significant gap between the level of funding needed for adaptation to climate change in poor developing countries, and the carbon funding level foreseen under the current rules of the UNFCCC flexible mechanisms.

The analyses presented in the previous sections summarize the many opportunities that the carbon market offers to project activities that focus on the rural poor in developing countries and their ability to contribute to global climate mitigation while enhancing their adaptation capacity. These opportunities comprise a wide range of options, from international climate policy agreements such as UNFCCC mechanisms to voluntary frameworks.

There is scope for enhancing carbon offsets from agriculture and forestry, by both increasing the numbers of these project categories, scaling up related activities, and widening their geographic distribution (FAO, 2010c). Importantly, the economic potential for additional carbon sequestration, including REDD+ and sustainable forest management actions, agroforestry techniques, soil conservation in agriculture and renewable energy from biomass, is substantial, corresponding to 5–10 billion t/CO_2e per year by 2030 at carbon market prices ranging from US$4–10 t/CO2e (IPCC AR4 WGIII). Therefore, annual financial flows from these offsets could be as high as US$20–100 billion in 2030, decisively helping to meet the expected costs of adaptation to climate change in developing countries discussed above (Tubiello *et al*., 2009).

Success at scaling up current site-based projects to regional activities will be necessary so as to increase the size of the land-based carbon market. Scaling up is to be achieved by 'mainstreaming' a number of mitigation strategies into regional and national-development policy 'themes'. The CDM Programme of Activities (PoA) provides exactly such a tool. Under the PoA, a policy or market entity, whether a local, regional, or national government, association, or corporation, would set a regional-wide theme that links development policy with mitigation. For instance, it may set forth a plan for regional adaptation activities, based on 'good agricultural practices', aimed at strengthening food security in the face of climate variability and change. A PoA offset project could, in this case, allow certification of the carbon credits associated with such large-scale adaptation solutions, provided it can be demonstrated that the plan would not have been implemented without the additional income from its associated carbon credits.

Many of these activities are currently allowed under a number of voluntary schemes and pilot funds, but are excluded from the CDM; the largest of the existing carbon markets. In particular, credits from REDD, as well as from a range of agricultural and forestry activities, have the potential to greatly increase carbon flows to developing countries. Significant efforts should therefore be directed towards implementing enhanced land-based mechanism for use within voluntary and post-2012 Kyoto carbon markets.

Because of the many synergies that exist between mitigation and adaptation in land-based systems, it has been suggested that specific project activities could be supported through monetization of both their mitigation and adaptation components (FAO, 2010a), i.e. through the development of special carbon credits, validated under a novel 'adaptation carbon' standard. These credits could be supported in part on the voluntary market, but especially in regulated post-Kyoto markets, for instance by requiring compliance buyers to include a percentage of such credits into their portfolios (i.e. FAO, 2008; Tubiello *et al*., 2009).

The Bali roadmap and the Cancun Agreements provide an important new focus on the synergies between adaptation and mitigation strategies, offering a unique window of opportunity for developing countries to identify, negotiate, and take advantage of enhanced and additional financial resources that could be used to help their rural poor reduce their vulnerability under climate change.

Under current financing mechanisms of the Kyoto Protocol, in particular the CDM and JI, as well as the GEF Adaptation Fund, significantly larger financial flows could be directed to helping developing countries in particular by focusing on agriculture and forestry sectors, which are often the main source of employment and income.

Important contributions already exist under a variety of voluntary carbon markets, typically established by private-public partnership, some of which focus on the linkages between carbon sequestration and sustainable development of relevance to rural communities. These markets should be enhanced in the future, and some of their approaches to mainstreaming mitigation into sustainable development could be used to complement and possibly expand current regulated mechanisms.

In conclusion, significantly larger financial flows than are possible under the current CDM and JI could be created by adding a range of land-based activities within post–2012 climate mitigation and adaptation mechanisms; in particular reduced deforestation and forest degradation (REDD+), agricultural land restoration and soil carbon sequestration, agroforestry, and land conservation practices.

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