IPCC WGII Fourth Assessment Report – Draft for Government and Expert Review

Chapter 5 – Food, Fibre, and Forest Products

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Executive Summary

Current sensitivity/vulnerability

- Recent extreme climate events demonstrate the current vulnerability of food, fibre, forestry and fisheries (FFFF) systems. The summer 2003 European heat wave and drought reduced maize yields by 20%, the largest yield decline since 1960 (*high confidence).* [Box 5.1]. Frequent droughts in Africa have caused high livestock mortality (*high confidence*) [see 5.2.1].

Assumptions about future trends

- Regional changes in JJA precipitation are likely to cause increased water deficit in some temperate and semi-arid regions, which are currently suitable for rainfed crops (*medium confidence)* [see 5.3.1].
- Future climate change is likely to result in shifts toward higher latitudes and elevations in the climatic suitability for FFFF production. (*high confidence)* [see 5.3.1].
- The impact of climate change on FFFF sectors should be seen against the expected long-term developments in the global economy, including increasing purchasing power and declining relative economic importance of these sectors. (*medium to high confidence)*[see 5.3.2.1] .
- Pressure to cultivate marginal land or to adopt unsustainable cultivation practices as yields drop may increase land degradation and endanger biodiversity of both wild and domestic species (*low confidence)* [see 5.3.2.1].

Key future impacts

- Recent results from Free Air Carbon Enrichment (FACE) studies of carbon dioxide fertilisation confirm conclusions from the TAR that crop yields at 550 ppm CO2 concentration increase by an average of 17%. [*medium confidence]* Crop model estimates of CO2 fertilisation are in the range of FACE results.(*high confidence)* [see 5.4.1].
- Results from the FACE studies of CO2 enrichment to 550 ppm on trees suggest a smaller effect than is simulated by some of the forest sector models, although no direct comparisons with these models have been done (*high confidence*) [see 5.4.1].
- An increased vulnerability of terrestrial carbon pools may be caused by the impacts of warming and droughts on soil carbon and by the increased risks of fires in forests with feedback to radiative forcing (*medium confidence*) [see 5.4.1].
- Crop modelling studies that include extremes in addition to changes in mean climate show lower yields than for changes in means alone (*medium confidence*). [see 5.4.1.3]
- In temperate regions, moderate to medium local increases in temperature (1 to 3ºC), along with associated CO2 increase and rainfall changes can have small beneficial impacts on crops, including wheat, maize, and rice. Cotton has a similar response. Further warming has increasingly negative impacts (*medium to low confidence*) [see Figure 5.2].
- In tropical regions, even moderate temperature increases are likely to have negative yield impacts for major cereals (1^oC for wheat and maize, 2^oC for rice). For temperature increases more than 3^oC impacts are stressful to all crops (*medium to low confidence*) [see Figure 5.2].
- Potential negative yield impacts are particularly pronounced in several regions where food security is already challenged and where the underlying natural resource base is already poor (*medium confidence)* [see 5.4.2.1].
- Climate changes increase irrigation demand in the majority of world regions due to a combination of increased evaporation arising from increased temperatures and, in some regions, decreased precipitation. This combines with increased water stress (see Chapter 3) to provide a significant challenge to future food security (*medium to high confidence)* [see 5.4.2.1].
- The role of pests has become clearer since the TAR. In the FFFF sectors, the poleward spread of diseases and pests which were previously found at lower latitudes is observed and predicted to continue. The magnitude of the overall effect is unknown, but is likely to be highly regionalized (*medium to high confidence*) [5.4.2.1].

- Warming and increased frequency of heat waves and droughts in Mediterranean, semi-arid and arid pastures will reduce livestock productivity, and increase heat stress—with potential increase in mortality (*medium to high confidence*) [see 5.4.3.1].
- In humid and temperate grasslands a moderate incremental warming (no change in variability) will increase pasture productivity and reduce the need for housing and for feed concentrates in some areas (*medium to high confidence*). However, a reduction of rainfall in some regions, with increased climate variability and extreme events, may suppress the positive effect of a moderate warming (*medium confidence*) [see 5.4.3.2].
- Elevated CO_2 and warming will modify the dominance of palatable plant species in pastures (*high confidence*). This confirms findings from TAR that feed quality for domestic herbivores will be affected both in terms of fine-scale (reduced protein content) and coarse-scale (plant species) changes [see 5.4.3.2].
- Overall, global forest products output during the 21st century changes, ranging from a modest increase to a slight decrease depending on the assumed impact of CO2 fertilisation and the effect of processes not well represented in the models (e.g., pest effects), although regional and local changes will be large. Production in some traditional forest production regions may decline as new ones benefit. (*medium confidence)* [see 5.4.5.1].
- Regional changes in the distribution and productivity of particular fish species will continue and local extinctions will occur at the edges of ranges, particularly in freshwater and diadromous species (e.g. salmon, sturgeon). In some cases ranges and productivity will increase (*high confidence)*[see 5.4.6.2].
- Emerging evidence suggests concern that meridional overturning circulation is slowing down, with serious potential consequences for fisheries (*low confidence)*[see 5.4.6.2].
- Smallholder and subsistence farmers, pastoralists and artisanal fisher people, whose adaptive capacity is constrained, will suffer complex, localized impacts of climate change, especially by extreme events and other impacts such as sea-level rise and snow-pack decrease. Vulnerability increases. (*high confidence)*[see 5.4.7].

Adaptation

- A large number of short-term responsive (or autonomous) adaptations are possible in cropping, grazing, forestry and fishery systems. Many of these are extensions of existing risk management activities (*high confidence)*[see 5.5.1].
- The potential effectiveness of the adaptations varies from only marginally reducing negative impacts to in some cases changing a negative impact into a positive impact. On average in cereal cropping systems adaptations such as changing varieties and planting times enable avoidance of a 10-15% reduction in yield. The benefit from adapting tends to increase with the degree of climate change up to a point *(medium to high confidence)* [see Figure 5.2].
- Changes in policies and institutions, including property rights, will be needed to facilitate adaptation to climate change. These could include greater investments in participatory research, infrastructure, capacity building, risk management, improved product storage and markets. The costs of implementing these adaptations will depend, in part, on the degree of mainstreaming with other policy initiatives (e.g., trade policy, investment in research and development) (*medium confidence*) [see 5.5.2].

Costs, vulnerability and other socioeconomic aspects

- Globally, an increased agricultural production potential should increase overall food availability in the short to medium-term (2020-2050), followed by a decline to 2080 (*medium to low confidence*) [see 5.6.1]. The global increase to 2050 will mask substantial regional differences (see tropical versus temperate crop yields above) (*medium confidence*).
- Projections of rising overall incomes imply a simultaneous increase in the capacity of individuals and countries to purchase food, although with regional differences. The increase in purchasing power for food is reinforced in the period to 2050 by declining real prices but would be adversely

affected by higher real prices for food from 2050 to 2080 (*low to medium confidence)* [see Figure 5.4].

- Agricultural trade flows are foreseen to rise significantly; climate change is expected to increase exports of temperate zone products to tropical countries (*medium confidence)* [see 5.6.3].
- Regional comparative advantage in forest production changes substantially in response to the changing climate and this is assisted by management, including an increasing role for planted forests. Such changes will change trade patterns with more exports from tropical and sub-tropical regions to temperate regions (*medium confidence).* This projected trend is sensitive to presumed trends in tropical deforestation [see 5.3.2.2, 5.6.2].

Sustainable development

- Adaptation measures must be carefully integrated with overall development goals expressed, for example, by the Millennium Development project [see 5.7].

5.1 Introduction: importance, scope and uncertainty, TAR summary, and methods

5.1.1 Importance of agriculture, forestry, and fisheries

At present, 40% of the Earth's surface is managed for cropland and pasture (Foley *et al.*, 2005). Natural forests cover another 30% (3.9 billion ha) of land; though only about 5% of forest cover is managed for forestry (about 200 M ha). In developing countries nearly 70% of people live in rural areas where agriculture is the largest supporter of livelihoods – growth in agricultural incomes in developing countries fuels the demand for non-basic goods and services, fundamental to human development. The FAO estimates that the livelihoods of roughly 450 million of the world's poorest people are entirely dependent on managed ecosystem services. Fish provide more than 2.6 billion people with at least 20 percent of their average per capita animal protein intake, but three-quarters of global fisheries are currently fully exploited, overexploited or depleted (FAO Fisheries Department, 2004).

5.1.2 Scope of the chapter and treatment of uncertainty

The scope of this chapter is:

For food crops, pastures and livestock, industrial crops and biofuels, forestry (commercial forests), aquaculture and fisheries, and small-holder and subsistence agriculturalists and artisanal fishers:
- To examine current climate sensitivities/vulnerabilities;
- To consider future trends in climate, global and regional food security, forestry, and fisheries production;
- To review key future impacts of climate change in food crops, pasture and livestock production, industrial crops and biofuels, forestry, fisheries, and small-holder and subsistence agriculture;
- To assess the effectiveness of adaptation in offsetting damages and to identify adaptation options, including planned adaptation to climate change;
- To examine the social and economic costs of climate change in those sectors;
- To explore the implications of responding to climate change for sustainable development;

We strive for consistent treatment of uncertainty in this chapter. Traceable accounts of final judgments of uncertainty in the findings and conclusions are, where possible, maintained. These accounts explicitly state sources of uncertainty in the methods used by the studies that comprise the assessment. At the end of the chapter, we summarize those findings and conclusions and provide a final judgment of their uncertainties.

5.1.3 Important findings of the TAR

The key findings of the Third Assessment Report with respect to food, fibre, forestry, and fisheries are an important benchmark for this chapter. In reduced-form, they are:

Food crops
- CO_2 effects increase with warmth but fall once optimal photosynthetic temperatures are exceeded. The CO_2 effect may be relatively greater – compared to irrigated crops – for crops under moisture stress.
- Modelling studies suggest crop yield losses with minimal warming in the tropics. Temperate crops benefit from a small amount of warming (~+2˚C) but decline after that.
- Countries with greater wealth and natural resource endowments adapt more efficiently than those with less.

Forestry

- Free-air CO_2 enrichment (FACE) experiments suggest that trees rapidly become acclimated to increased CO_2 levels.
- The largest impacts of climate change are likely to occur earliest in boreal forests.
- Contrary to the SAR, climate change will increase global timber supply and enhance existing market trends toward rising market share in developing countries.

Aquaculture and Fisheries

- Global warming will confound the impact of natural variation and fishing activity and make management more complex.
- The sustainability of the fishing industries of many countries will depend on increasing flexibility in bilateral and multilateral fishing agreements, coupled with international stock assessments and management plans.
- Increases in seawater temperature have been associated with increases in diseases and algal blooms in the aquaculture industry.

5.1.4 Methods

Research on the consequences of climate change for agriculture, forestry, and fisheries is addressing deepening levels of system complexity that requires a new suite of methodologies to cope with the added uncertainty that accompanies the addition of new, often non-linear, process knowledge. The application of meta-analysis to agriculture, forestry, and fisheries in order to identify trends and consistent findings across large numbers of studies that address a common research problem has revealed important new information since the Third Assessment Report (TAR), especially on the direct effects of atmospheric CO_2 on crop and forest productivity (e.g., Long, 2005) and fisheries (Allison *et al.*, 2005). The complexity of processes that determine adaptive capacity has dictated an increasing regional focus to studies in order best to understand and predict adaptive processes (Kates and Wilbanks, 2003)—hence the rise in numbers of regional-scale studies. This heightens the need for robust methods of scaling local and regional findings to larger, often political, regions for use in decision making (Easterling and Polsky, 2004). Further complexity is contributed by the expansion of scenarios of future climate and society (Nakicenovic and Swart, 2000).

5.2 Current sensitivity, vulnerability, and adaptive capacity to climate

5.2.1 Current sensitivity

The inter-annual, monthly and daily distribution of climate variables (e.g. temperature, radiation, precipitation, water vapour pressure in the air, and wind speed) affects a number of physical, chemical and biological processes that drive the productivity of agricultural, forestry and fisheries systems. The latitudinal distribution of crop, pasture and forest species is a function of the current climatic and atmospheric conditions as well as photoperiod (e.g. Leff *et al.*, 2004). Crops exhibit threshold responses to their climatic environment that affect their growth, development and yield (Porter and Semenov, 2005). Yield damaging climate thresholds for cereals and fruit trees include absolute temperature levels that are linked to particular developmental stages that condition the formation of reproductive organs, such as seeds and fruits and can be effective over short time-periods (Wollenweber *et al.*, 2003; Wheeler *et al.*, 2000). This means that yield damage estimates from coupled crop–climate models need to have a maximum temporal resolution of a few days and include detailed phenology (Porter and Semenov, 2005). Short-term natural extremes such as storms and floods, inter-annual and decadal climate variations as well as large-scale circulation changes such as the El Niño Southern Oscillation (ENSO) all have important effects on crop, pasture and forest production

(Tubiello, 2005). For example, Nelson and Kokic, found that El Niňo-like conditions result in a greater than 75 per cent chance of farm incomes falling below their long term median across most of the twelve Australian cropping regions with impacts on GDP ranging from 0.75 to 1.6% (O'Meagher, 2005).

There are a number of examples, both in temperate and in tropical regions, of large impacts on the food, feed and fibre production of extreme climatic events. One example given here is the heat wave during the summer 2003 in Europe (Box 5.1), and another is the high mortality and reduced productivity of livestock during drought events in Africa during the last 25 years (Table 5.1).

Box 5.1 European heat wave impact on the agricultural sector.

Europe experienced a particularly extreme climate event during the summer of 2003, with temperatures up to 6°C above long-term means, and precipitation deficits up to 300 mm y^{-1} (see WG I report). A record crop yield drop of 36% occurred in Italy for corn grown in the Po valley where extremely high temperatures prevailed (Ciais *et al.*, 2005). In France, compared to 2002, the corn grain crop was reduced by 30% and fruit harvests declined by 25%. Winter crops (wheat) had nearly achieved maturity by the time of the heatwave and therefore suffered less yield reduction (21 % decline in France) than summer crops (like corn, fruit trees and vines) undergoing maximum foliar development (Ciais *et al.*, 2005). Forage production was reduced on average by 30% in France and hay and silage stocks for winter were partly used during the summer (COPA COGEGA, 2003a). Wine production in Europe was the lowest in 10 years (COPA-COFEGA, 2003B). The economic losses for the agriculture sector in the European Union were estimated at 13 billion Euros, with largest losses in France (4 billion Euros) (Sénat, 2004). The estimation of forest area destroyed reached 647,069 hectares. Portugal was the worst hit with 390,146 ha burned, destroying around 5.6 % of its forest area. Spain came second with 127,525 ha burned. The agricultural area burned reached 44,123 ha plus 8,973 ha of unoccupied land. This was by far the worst forest fire season that Portugal had faced in the last 23 years (EU-JRC, 2003).

Table 5.1: Quantified impacts of selected African droughts on livestock, 1981-1999.

1981-84	Botswana	20% reduction in national herd	FAO, 1984 cited in Toulmin, 1986
1982-84	Niger	62% loss of national cattle herd	Toulmin, 1986
1983-84	Ethiopia (Borana Plateau)	90% of calves, 45% cows, 22% mature males	Coppock, 1994
1983-85	Ethiopia (Borana)	37% of cattle	Desta and Coppock, 2002
1991	Northern Kenya	Cattle 556,000 (28%) Sheep and Goats 723,000 (18%)	Surtech, 1993 cited in Barton and Morton, 2001
1991-93	Ethiopia (Borana)	42% of cattle	Desta and Coppock, 2002
1993	Namibia	22% of cattle 41% of goats and sheep	Devereux and Tapscott, 1995
1995-97	Greater Horn of Africa (average of 9 areas)	29% of cattle 25% of sheep and goats	Ndikumana *et al.*, 2000
1995-97	Southern Ethiopia	78% of cattle 83% of sheep and goats	Ndikumana *et al.*, 2000
1998-99	Ethiopia (Borana)	62% of cattle	Shibru, 2001 cited in Desta and Coppock, 2002

5.2.2 Sensitivity to multiple stresses

Multiple stresses such as limited availability of water resources (see Chapter 3), loss of biodiversity (see Chapter 4), and air pollution (Box 5.2) are increasing climate sensitivity and climate stress in the agricultural sector (FAO, 2003). Natural land resources are being degraded through soil erosion; salinization of irrigated areas; dry-land degradation from overgrazing; over-extraction of ground water; growing susceptibility to disease and build-up of pest resistance favoured by the spread of monocultures and the use of pesticides; loss of biodiversity and erosion of the genetic resource base when modern varieties displace traditional ones (FAO, 2003). The sum total effect of these processes on agricultural productivity is not clear. In forestry, fires, insect outbreaks, air pollution and soil degradation increase the sensitivity to climate variability (see 5.3.4). In fisheries, overexploitation of stocks (see 5.3.6), loss of biodiversity, water pollution and changes in water resources (see Box 5.3) also increase the current sensitivity to climate.

Box 5.2 Air pollutants and UV-B

Ozone has significant adverse effects on crop yields, pasture and forest growth and species composition (Ashmore, 2005; Vandermeiren, 2005; Volk, 2006; Loya *et al.*, 2003). While emissions of ozone precursors, chiefly NOx compounds, may be decreasing in North America and Europe due to pollution control measures, they are increasing in other regions of the world—especially Asia. Additionally, as global ozone exposures increase over this century, direct and indirect interactions with climate change and elevated CO_2 will further modify plant dynamics (Booker, 2005; Fiscus, 2004). Although several studies confirm TAR findings that elevated CO_2 may ameliorate otherwise negative impacts from ozone (Kaakinen, 2004), the essence of the matter should be viewed the other way around: increasing ozone concentrations in future decades, with or without CO_2, with or without climate change, will negatively impact plant production, possibly increasing exposure to pest damage (Karnoski, 2003, 2002; Ollinger, 2002). Current risk assessment tools do not sufficiently consider these key interactions. Improved modeling approaches linking the effects of ozone, climate change, nutrient and water availability, on individual plants, species interactions and ecosystem function are needed (Ashmore, 2005), and some efforts are under way (Felzer, 2004). Finally, impacts of UV-B exposure on plants was previously reviewed by the TAR, showing contrasting experimental results on the interactions of UV-B exposure with elevated CO_2. Post TAR studies have not narrowed uncertainty, with some findings suggesting amelioration of negative UV-B effects by elevated CO_2 (Qaderi and Reid, 2005), and others showing no effect (Zhao *et al.*, 2003).

5.2.3 Current vulnerability and adaptive capacity in perspective

Current vulnerability to climate variability, including extreme events, is both hazard- and context-dependent (Brooks *et al.*). For agriculture, forestry and fisheries systems, vulnerability depends on exposure and sensitivity to climate conditions (as discussed above), and on the capacity to cope with or adapt to changing conditions. A comparison of conditions on both sides of the United States-Mexico border reveal important differences in access to resources, state involvement, class and ethnicity, which result in drastically different vulnerabilities for farmers and ranchers living within the same biophysical context (Vasquez-Leon *et al.*). Processes linked to globalization are also changing the capacity to respond to climate variability and there is a growing recognition that efforts to reduce vulnerability and facilitate adaptation to climate change must be linked to the processes of reform underway in both developing and industrialized countries (Eakin and Lemos, 2006).

Adaptive capacity with respect to current climate is dynamic, and influenced by changes in wealth, human capital, information and technology, material resources and infrastructure, institutions and entitlements (see Chapter 17) (Yohe and Tol, 2001; Eakin and Lemos, 2006). The production and dissemination of seasonal climate forecasts has improved the ability of many resource managers to anticipate and plan for climate variability, particularly in relation to the El Niño-Southern Oscillation (ENSO) (Harrison, 2005). However, problems related to infectious disease, conflicts and other societal factors may decrease the capacity to respond to variability and change at the local level, thereby increasing current vulnerability. Policies and responses made at the national and international levels also influence local adaptations (Salinger *et al.*, 2005). National agricultural policies are often developed on the basis of local risks, needs, and capacities, as well as international markets, tariffs, subsidies, and trade agreements (Burton and Lim, 2005).

Sub-Saharan Africa is one area of the world that is currently highly vulnerable to food insecurity (Vogel, 2005). Drought conditions, flooding, and pest outbreaks are some of the current stressors to food security that may be influenced by future climate change. Current response options and overall development initiatives related to agriculture, fisheries, and forestry may be aggravated by health status, lack of information and ineffective institutional structures and processes, with potential negative outcomes for future adaptation to periods of heightened climate stress (Reid and Vogel, 2006). Sub-Saharan Africa is but one example.

5.3 Assumptions about future trends in climate, food, forestry, and fisheries

Declining global population growth (UN, 2004), rapidly rising urbanization, shrinking shares of agriculture in the overall formation of incomes and fewer people dependent on agriculture are amongst the key factors that are likely to shape the socio-economic environment in which climate change is likely to evolve. This environment will determine how climate change affects agriculture, how rural populations can cope with changing climate conditions and it will affect their ability to feed themselves. Any assessment of climate change impacts on agro-ecological conditions of agriculture must be undertaken against this background of changing socio-economic environment (Bruinsma, 2003).

5.3.1 Climate

Globally, some 3.6 billion ha (about 27% of the Earth's land surface) are too dry for rain-fed agriculture. Considering water availability, only about 1.8% of these dry zones are suitable for producing cereal crops under irrigation (Fischer *et al.*, 2002). In many other areas, water resources are already stressed and are highly vulnerable, with intense competition for water supply (FAO, 2003). Total seasonal precipitation as well as its pattern of variability (Olesen and Bindi, 2002) are both of major importance for agricultural, pastoral and forestry systems. Prevailing temperatures determine crop performance when moisture conditions are met. Similarly, when temperature requirements are met, the growth of a crop is dependent on how well its growth cycle fits within the period when water is available. The current climate, soil and terrain suitability for a range of rainfed crops and pasture types has been estimated by Fischer *et al.* (2002) (Figure 5.1b).

There is now greater confidence from global and regional-scale models concerning projected patterns of change in average precipitation than in the TAR. Decreases in precipitation are robustly predicted by more than 90% of the simulations by the end of the 21st century for the northern and southern subtropics (WG I, Summary for Policy Makers). Decreases are also expected for parts of western North and South America, and southern Europe, with increases expected in some places in the tropics as well as at higher latitudes (Figure 5.1a). Summer rainfall decline is projected to affect some major rainfed crop and pasture production areas in South America, South and North Africa, Australia and Southern Europe (Figure 5.1b). Extremes of precipitation increase are also very likely in major agricultural production areas in Southern and Eastern Asia, in East Australia and in Northern Europe (see WG I, Chapter 11 report). More frequent droughts are predicted in the Mediterranean area, in Central America, in Australia and New-Zealand (Figure 5.1a). It should be noted that climate change impact models for food, feed and fibre do not yet include these findings on projected patterns of change in precipitation, so the best we can do at present is to examine Figure 5.1a and b side by side.

(a)

Note: Figure 5.1a to be used with permission of Working Group 1.

(b)

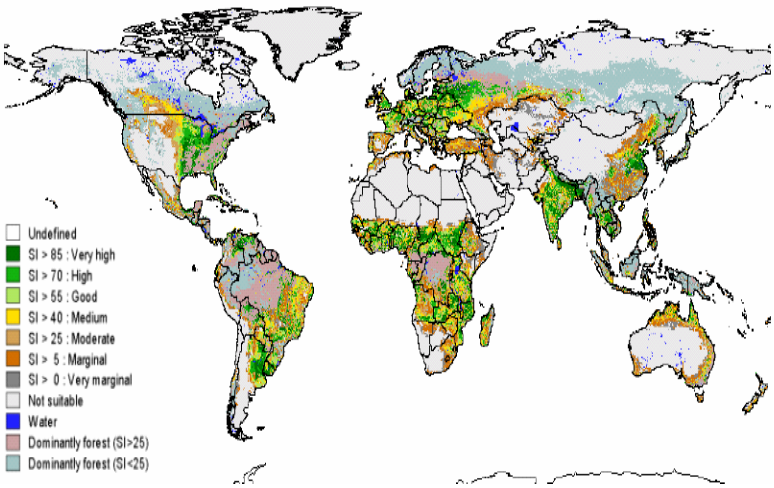


Figure 5.1: *a) Map of spatial patterns of projected rainfall change (from Summary for Policy Makers of WG I Fourth Assessment Report). b) Current suitability for rainfed crops (excluding forest ecosystems) (after Fischer, 2002).*

5.3.2 Balancing future global supply and demand in agriculture and forestry

5.3.2.1 Agriculture

Slower population growth and an increasing share of better-fed people (e.g. over half of the population in developing countries now already lives in countries averaging over 2700 kcal/person/day) is projected to lead to a gradual deceleration in the growth of global food demand. In parallel with the slow-down in demand, FAO (FAO, 2006) expects growth in world agricultural production to decline from 2.2% p.a. over the last 30 years to 1.6% p.a. in 2000-15, 1.3% p.a. in 2015-30 and 0.8% p.a. in 2030-50. This still implies a 55% increase in global crop production by 2030 and an 80% increase to 2050 (compared with 1999/01). To facilitate this growth in output, another 185 million ha of rain-fed crop land (+19%) and another 60 million ha of irrigated land (+30%) will have to be brought into production. Essentially the entire land expansion will take place in developing countries, most of it in sub-Saharan Africa and Latin America, which could result in direct tradeoffs with ecosystem services (Cassman *et al.*, 2003). In addition to expanded land use, yields are expected to rise. Cereal yields in developing countries are projected to increase from 2.7 tonnes/ha now to 3.8 tonnes/ha in 2050 (FAO, 2006).

These improvements in the global supply-demand balance will be accompanied by a further decline in the number of undernourished from more than 800 million at present to about 300 million people, or 4% of the population in developing countries, by 2050 (FAO, 2006). Notwithstanding these overall improvements, important food security problems remain to be addressed at the local and national level. Areas in sub-Saharan Africa, Asia and Latin America, with high population growth rates and high rates of natural resource degradation, are likely to continue to have high rates of poverty and food insecurity

(Alexandratos, 2005). Cassman *et al.*, (2003) emphasize that climate change will add to the dual challenge of meeting food (cereal) demand while at the same time protecting natural resources and improving environmental quality in these regions.

5.3.2.2 Forestry

A number of long-term studies of supply and demand of forestry products have been undertaken in recent years (e.g., Sedjo and Lyon, 1990, 1996; FAO, 1998; Hagler, 1998; Sohngen *et al.*, 1999; Sohngen *et al.*, 2001). These studies have projected a shift from natural forest harvests to those of plantations. For example, Hagler (1998) suggested growth of the industrial wood harvest produced on plantations from 20% in 2000 to over 40% in 2030, while the FAO (2004a) estimates that in 2001 the plantations already produced about 34%, and this portion may increase to 44% by 2020 (Carle *et al.*, 2002) and 75% by 2050 (Sohngen *et al.*, 2001). There also will be a global shift in the industrial wood supply between the temperate and tropical zones and also between the Northern and Southern Hemispheres, which in turn will increase trade in forest products in order to balance the regional imbalances in demand/supply (Hagler, 1998) .

In recent decades forecasts of industrial wood demand have tended to be consistently higher than actual demand (Sedjo and Lyon, 1996), with very slow demand increase (compare current demand of 1.6 B m^3 to 1.5 B m^3 in the early 1980s [FAO selected issues]). The recent projections of the FAO, Häggblom (2004); Sedjo and Lyon (1996); and Sohngen *et al.* (2001) project similar modest demand growth to 1.8 – 1.9 B m3 by 2010 – 2015 - compare to earlier higher predictions of 2.1 B m3 by 2015 and 2.7 B m^3 by 2030 (Hagler, 1998). Similarly, an FAO (2001) study suggests that global fuelwood use has peaked at 1.9 B m^3 and is stable or declining, but the use of charcoal continues to rise (e.g., Arnold *et al.*, 2003). However, fuelwood use could dramatically increase in the face of rising energy prices, particularly if incentives are created to shift away from fossil fuels and toward biofuels. There are many other products and services that depend upon forest resources than above. However, there are not any satisfactory estimates on the global future demand of these products and services.

Finally, although climate change will impact the availability of forest resources, the anthropogenic impact, particularly land use change and deforestation in tropical zones is likely to be extremely important (Zhao *et al.*, 2005). In the Amazon basin, deforestation and increased forest fragmentation may impact water availability, triggering more severe droughts. Droughts combined with deforestation in turn increases fire danger (Laurance and Williamson, 2001): simulations show that during the 2001 ENSO period approximately one-third of Amazon forests became susceptible to fire (Nepstad *et al.*, 2004).

5.3.2.3 Fisheries

Global food fish production is forecast to increase but not as fast as the world demand to 2020. Per capita fish consumption and fish prices are expected to rise, with wide variations per commodity type and region. By 2020, wild capture fisheries are predicted to continue to supply most of the fish produced in sub-Saharan Africa (98%), the USA (84%), Latin America (84%), but not India (45%) where aquaculture production will dominate (Delgado *et al.*, 2003). In Asia, all countries are likely to produce more fish between 2005 and 2020, but the rate of increase will slow down. Trends in capture fisheries (usually zero growth or modest declines) will not unduly endanger overall fish supplies; however, any decline of fisheries is a cause for concern given the potential repercussions for fish consumption (Briones *et al.*, 2004).

5.3.2.4 Subsistence and smallholder agriculture

“Subsistence and smallholder agriculture” is used here to describe rural producers, predominantly in developing countries, who farm using mainly family labour and for whom the farm provides the principal source of income (Cornish, 1998). Pastoralists and people dependent on artisanal fisheries and household aquaculture enterprises Allison and Ellis (2001) are also included in this category.

There are few informed estimates of world or regional population of these categories (Lipton, 2004). While not all smallholders, even in developing countries, are poor, 75% of the world's 1.2 billion poor (defined as consuming less than one purchasing-power adjusted dollar per day) live and work in rural areas (IFAD, 2001). They suffer, in varying degrees, problems associated both with subsistence production (isolated and marginal location, small farm-size, informal land tenure, low levels of technology), and with uneven and unpredictable exposure to world markets. These systems have been emphasized as "complex, diverse and risk-prone" (Chambers *et al.*, 1989). Production systems are complex and diverse: in the combinations of plant and animal species that are exploited; the types of integration between them; their production objectives; and their institutional arrangements for managing natural resources. Risks are also diverse—drought and flood, crop and animal diseases, and market shocks—and may be felt by individual households or entire communities. Smallholder and subsistence farmers and pastoralists often practice hunting/gathering of wild resources as well as crop and livestock production, to fulfil energy, clothing and health needs as well direct food requirements. They also widely participate in off-farm and/or non-farm employment.

Subsistence and smallholder livelihood systems currently experience a number of interlocking stressors other than climate change and climate variability, as outlined in section 5.2.2 above. They also possess certain important resilience factors: efficiencies associated with the use of family labour (Lipton, 2004), livelihood diversity allowing spreading of risks, and indigenous knowledge allowing exploitation of risky environmental niches and coping with crises. The combinations of stressors and resilience factors give rise to complex positive and negative trends in livelihoods. Rural-urban migration will continue to be important; the World Bank estimates that 90 percent of population growth in developing countries occurs in urban areas. Within rural areas there will be continued diversification away from agriculture: already non-farm activities account for 30-50% of rural income in developing countries (Davis, 2004). Although Vorley (2002), Hazell (2004), and Lipton (2004) see the possibility, given appropriate policies, of pro-poor growth based on the efficiency and employment generation associated with family farms, it is overall likely that smallholder and subsistence households will decline in numbers, as they are pulled or pushed into other livelihoods, with those that remain suffering increased vulnerability and increased poverty. Because of waning numbers of small-holder and subsistence households, projections for these categories will be progressively less meaningful in the medium-term.

5.4 Key future impacts, vulnerabilities, and their spatial distribution

5.4.1 Primary effects and interactions

The TAR concluded that climate change and variability will impact food, fibre and forests around the world due to the effects on plant growth and yield of elevated CO_2, higher temperatures, altered precipitation and transpiration regimes, increased climate variability, as well as modified weed, pest and pathogen pressure. Many studies since the TAR confirmed and extended previous findings; key issues are described in the following sections.

5.4.1.1 Re-analysis of CO_2 effects suggests that they may be lower in the field

Plant response to elevated CO_2 alone—without climate change—is positive and was reviewed extensively in the TAR. Effects will depend on photosynthetic pathway, species, growth stage, and management (Ainsworth and Long, 2005; Norby *et al.*, 2003; Jablonski *et al.*, 2002). Recent re-analyses of FACE data sets confirmed TAR reviews, indicating on average, across crops, +17% yield increases at 550 ppm (Long *et al.*, 2004); and increases in above-ground biomass at 550 ppm for trees (+28%), legumes (+24%) and pastures (+10%) (Nowak *et al.*, 2004; Ainsworth *et al*., 2003). For commercial forestry, slow-growing species may respond little to elevated CO_2 (e.g., Vanhatalo *et al.*, 2003), and fast-growing trees more strongly, with harvestable wood increases of +15-25% at 550 ppm and high N (Wittig *et al.*, 2005; Liberloo *et al.*, 2005; Calfapietra *et al.*, 2003).

How current models simulate responses to CO_2 is now questioned (Ainsworth and Long, 2005). However, our assessment is that main crop simulation models, such as CERES, Cropsys, EPIC, SoyGrow, and main pasture models CENTURY and EPIC, are in line with recent findings—in fact a bit lower—by assuming crop yield increases of about 8-17% (Tubiello *et al.*, 2006; Tubiello and Ewert, 2002), and above-ground grassland production of about +15-20%, at 550 ppm. By contrast, comparisons of forestry model predictions with observed data under elevated CO_2 is still insufficient to draw similar conclusions.

Importantly, plant physiologists and modelers alike now recognize that effects of elevated CO_2 measured in experimental settings and implemented in models may overestimate actual field and farm-level responses, due to many limiting factors such as pests, weeds, competition for resources, soil water and air quality, etc., which are neither well understood at large scales, nor well implemented in leading models (Korner, 2005; Ainsworth and Long, 2005; Tubiello and Ewert, 2002; Peng *et al.*, 2004; Ziska, 2004; Karonsky, 2003; Fuhrer, 2003). Assessment studies should therefore include these factors where possible, while analytical capabilities need to be enhanced; yield and production projections should use a range of parameterisations of CO_2 effects to better convey the uncertainty range.

5.4.1.2 Interactions of elevated CO_2 with temperature and precipitation may critically modify impacts on production

Many recent studies confirm and extend TAR findings that temperature and precipitation changes in future decades will modify—and often limit—direct CO_2 effects on plants. For instance, high temperatures during flowering may lower CO_2 effects by reducing grain number, and size and quality (Caldwell *et al.*, 2005; Baker, 2004; Thomas *et al.*, 2003). Increased water demand under warming may also reduce CO_2 effects. Rainfed wheat grown at 450 ppm CO_2 showed yield increases up to 0.8°C warming, then declines beyond 1.5°C warming; additional irrigation was needed to counterbalance these negative effects (Xiao *et al.*, 2005). In pastures, elevated CO_2 together with increases in temperature, precipitation, and N deposition resulted in increased primary production, with changes in species distribution and litter composition (Aranjuelo *et al.*, 2005; Henry *et al.*, 2005; Zavaleta *et al.*, 2003; Shaw *et al.*, 2002). Future CO_2 levels may favour C_3 plants over C_4 (Demer, 2003); yet the opposite is expected under associated temperature increases (Shukla, 2003); the net effect remains uncertain.

Finally, precipitation changes may modify ecosystem productivity and function, particularly in marginal areas; higher water-use efficiency and greater root densities under elevated CO_2 in crops, pasture and forestry systems may in some cases alleviate drought pressures, although large-scale dynamics are not well understood (Centritto, 2005; Norby *et al.*, 2004; Shafer *et al.*, 2002; Wullschleger *et al.*, 2002). Thus climate impacts may significantly depend on the precipitation scenario considered. In particular, since more than 80% of total agricultural land—and close to 100% pastureland—is rainfed, GCM-dependent changes in evaporation to precipitation ratios will often shape both the direction and magnitude of the overall impacts (Tubiello *et al.*, 2002, Olesen and Bindi, 2002).

5.4.1.3 Increased variability of extreme events may further damage plant production

The TAR already reported on studies documenting additional negative impacts of increased climate variability on plant production under climate change, beyond those estimated from changes in mean variables alone. More studies since the TAR have more firmly established such issues (Porter and Semenov, 2005); they are described in detail in sections 5.4.2 to 5.4.7 in this chapter. Understanding links between increased climate variability and ecosystem disturbance—fires, pest outbreaks, etc.—is particularly important (Hogg and Bernier, 2005; Volney, 2006; Carroll, 2004). We note here that although a few models since the TAR have started to incorporate impacts of increased climate variability on plant production, most assessment studies continue to only include effects on changes in mean variables.

5.4.1.4 Impacts on pests and diseases and animal health

The importance of weeds, pest and disease interactions with climate change was reviewed in the TAR. New research identified CO_2/temperature interactions as one important factor determining plant damage due to pests in future decades; CO_2/precipitation interactions will be likewise important, but no quantitative analyses exist to date (Zvereva and Kozlov, 2006; Chen *et al.*, 2004; Stacey and Fellows, 2002). Most studies continue to investigate pest damage as a separate function of either CO_2 (Agrell *et al.*, 2004; Chakraborty and Datta, 2004; Chen *et al.*, 2005b; Chen *et al.*, 2005a) or climate—mostly temperature (Cocu *et al.*, 2005; Bale *et al.*, 2002). For instance, recent warming trends in the U.S. and Canada have led to earlier insect spring activity and proliferation of some species, such as the mountain pine beetle (e.g., (Crozier, 2002, see also Ch.1). Importantly, increased climate extremes may promote plant disease and pest outbreaks (Alig and al., 2004; Gan, 2004). Finally, new since the TAR are studies focusing on the spread of animal diseases and pests from low to mid-latitudes due to warming, a continuance of trends already under way (see 5.2). For instance, models project that *bluetongue*, affecting mostly sheep, occasionally goat and deer, would spread from the tropics to mid-latitudes (Hendrick, 2005). Likewise, White *et al.*, in press simulated under climate change increased vulnerability of the Australian beef industry to the cattle tick (*Boophilus microplus*). Most assessment studies do not explicitly consider either pest-plant dynamics or impacts on livestock health as a function of CO_2 and climate.

5.4.1.5 Vulnerability of carbon pools

Vulnerability of organic carbon pools to climate change in managed systems is an important topic due to its linkage with land sustainability and climate mitigation actions. The TAR had reviewed potential dynamics that might either increase or decrease carbon pools in agricultural fields, pastures and managed forests. Recent research confirms results—and the uncertainties—of previous findings, i.e., carbon storage in particulate soil organic matter pools is often increased under elevated CO_2 in the short term (e.g. Allard *et al.*, 2005). However the total soil C sink may become saturated at elevated CO_2 concentrations (Gill *et al.*, 2002) when nutrients inputs are low (Van Groeningen *et al*., 2006). More research is needed to lower current uncertainty and elucidate specific key issues: for instance the impacts of increased climate variability on stability of carbon and soil organic matter pools. The recent European heat wave of 2003 led to significant soil carbon losses (Ciais *et al.*, 2005). Also of importance are interactions with air pollution—ozone significantly limited enhanced C-sequestration rates under elevated CO_2 (Loya *et al.*, 2003)—as well as the links between land use change, adaptation, carbon sequestration and long-term sustainability of managed production systems (e.g., Rosenzweig and Tubiello, 2006). Because of the large land area covered by forestry, pastures and crops, the potential for climate change to greatly affect the terrestrial C sink (Ciais *et al.*, 2005) and thereby to further increase the atmospheric CO_2 concentration (Betts *et al.*, 2004) should be emphasized.

5.4.1.6 Remaining Uncertainties

Understanding key dynamics in CO_2/climate interactions, pest weed and disease, and climate variability/ecosystem vulnerability remains a priority for understanding future impacts on managed systems. Additional experiments and simulations are necessary; however, reducing uncertainties requires increased independent replication of similar experiments; renewed model inter-comparison efforts; and continued model development and evaluation of complex managed system dynamics. Design of better integrated experimental and modeling projects – spanning relevant temporal and spatial scales – may be one way to better test, evaluate and further develop our assessment tools.

5.4.2 Food-crop farming including tree crops

Simulation results of crop models and integrated assessments– at scales from local to regional and global– reported in the TAR indicated that impacts on food systems might be small overall in the first half of the 21st century, but progressively negative after that, as mean temperatures increase regionally and globally above 2.5°C. Importantly, crop production in (mainly tropical) developing countries would suffer more than in (mainly temperate-zone) ones, due to a combination of adverse agro-climatic, socio-economic and technological conditions already present today, and their continued poor state in coming decades, compared to developed regions (see recent analyses in Alexandratos, 2005 and XiongWei, 2005).

Uncertainties remained in several areas, including: the true strength and saturation point of the elevated CO_2 response of crops grown in real fields; water relations and water availability, irrigation; interactions with weeds, pathogens and disease; importance of changes in variability versus changes in mean climate; implementation of CO_2 effects in models, and other scale/validation issues; socio-economic scenario-climate change interaction within integrated assessments, and their validation; and timing and implementation of adaptation strategies. In addition, the TAR covered impacts under mitigation scenarios only marginally; as well as the interactions of adaptation and mitigation strategies.

5.4.2.1 What is new since the TAR

Many studies since the TAR have confirmed key dynamics of previous regional and global projections. Importantly, many have contributed new knowledge—and reduced uncertainty—with respect to several of the issues identified above.

New Knowledge: *Increases in climate variability may lower crop yields beyond the impacts of mean climate change.* The TAR had concluded that crop losses could rise due to increases in climate variability under climate change. More frequent extreme events may indeed lower long-term yields by directly damaging crops at specific developmental stages, such as temperature thresholds during flowering (Porter and Semenov, 2005; Tubiello, 2005), or by making the timing of field applications more difficult, thus reducing the efficiency of farm inputs (Antle *et al.*, 2004). A number of simulation studies since the TAR has developed specific aspects of increased climate variability within climate change scenarios. Rosenzweig *et al.* (2002) computed that, under scenarios of increased heavy precipitation, production losses due to excessive soil moisture—already significant today—would double in the U.S. to $ 3 billion per year in 2030. Monirul and Mirza (2002) computed increased risk of crop losses in Bangladesh from higher flood frequency under climate change. In scenarios with higher rainfall intensity, Nearing *et al.* (2004) projected increased risks of soil erosion, while van Ittersum (2004) simulated a higher possibility of salinization in arid and semi-arid regions, due to increased loss of water past the crop root zone. Others have focused on the consequences of higher temperatures on the frequency of heat stress during growing seasons, as well on the frequency of frost occurrence during critical growth stages (Howden, 2003b).

New Knowledge: *Impacts of climate change on irrigation water requirement may be large.* A few new studies have further quantified the impacts of climate change on regional and global irrigation requirements. Döll (2002), considering direct impacts of climate change on crops evaporative demand, estimated an increase of *net* crop irrigation requirements, i.e., net of transpiration losses, of +5% to +8% globally by 2070, with larger regional signals, e.g., +15% in southeast Asia. Fischer *et al.* (2006), considering both increased evaporative demands and longer growing seasons under future warmer climates, computed increases in global net irrigation requirements of +20% by 2080 due to climate change, with larger impacts in developed vs. developing regions. Fischer *et al.* (2006) also projected increases in water stress—the ratio of irrigation withdrawals to renewable water resources—in the Middle East and southeast Asia, in agreement with independent findings (Arnell, 2004). Recent regional studies have likewise underlined critical climate change/water dynamics in key irrigated areas, such as North Africa (increased irrigation requirements; Abou-Hadid *et al.*, 2003) and China (decreased requirements; Tao *et al.*, 2003).

New Knowledge: *Elevated CO_2 and warmer temperatures combine to increase pest damage*. Research on interactions of elevated CO_2/temperature, weeds pest and disease has significantly increased since the TAR (e.g., Zvereva and Kozlov, 2006; Chen *et al.*, 2004; Stacey and Fellows, 2002), showing in particular that the interactions of elevated CO_2 and higher temperatures may significantly increase crop damage from pest herbivores in future decades.

New Knowledge: *Stabilization of CO_2 concentrations reduces damage to crop production*. Recent work further investigated the effects of mitigation – in the form of stabilization of atmospheric CO_2 – on regional and global crop production. Compared to business as usual scenarios, (Parry *et al.*, 2005) computed somewhat smaller impacts of climate change on crop production under 750 ppm CO_2 stabilization, and significantly reduced impacts under 550 pm stabilization, leaving lower risks of hunger. Tubiello and Fischer (2006) simulated beneficial effects of stabilization at 550 ppm, but with complex spatial and temporal dynamics: global costs of climate change to the agricultural sector were reduced in 2080 by 70-100% compared to the case with no mitigation. They found larger benefits in developing vs. developed countries, while the number of people at risk of hunger was cut by 60-85%. In the first decades of this century, however, some regions were projected to be worse-off with mitigation than without, due to lower CO_2 levels – thus reduced stimulation of crop yields – but same degree of climate change, compared to the unmitigated scenarios. Finally, adaptations to climate change are likely to happen at the same that mitigation strategies are implemented. A growing body of work has started to analyze potential synergies and incompatibilities of these two strategies (see Ch. 18 WGII).

TAR Confirmation: *Choice of spatial and temporal scale may affect crop modelling results*. More studies since the TAR have investigated impact dynamics as a function of spatial scale, confirming TAR findings that simulated climate impacts are greater when fine-scale vs. coarse-scale scenarios are used (e.g., Carbone *et al.*, 2003; Doherty *et al.*, 2003), possibly due to different patterns of moisture stress, timing and degree of temperature change during key growth phases in the different representations. Additional simulations are still needed to confirm such findings.

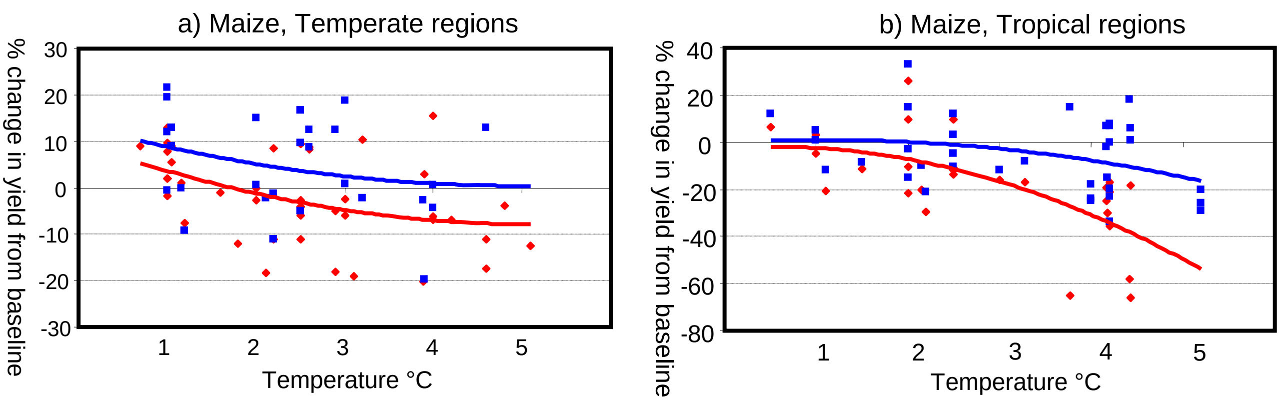
TAR Confirmation: *Trade lessens regional and global impacts*. Recent work by Fischer *et al.* (2005); Fischer *et al.* (2002); Parry *et al.* (2005); Parry (2004), confirm that global impacts on agriculture may be small over this century, once dynamics of economic adjustments and trade are considered. Yet despite socio-economic development, temperate countries would mostly benefit, while poor tropical countries would in general suffer from climate change, and increased malnutrition in Africa. Other studies, performed at either regional or global levels with various linkages between economics and trade, also indicated that developing regions may be more negatively affected than others (Mendelsohn *et al.*, 2004, Antle *et al.*, 2004, Reilly *et al.*, 2003; Cassman *et al.*, 2003; Olesen and Bindi, 2002). Finally, coupled agronomy-trade simulations show that socio-economic drivers such as increased food demand and improvements in production technology and efficiency need to be considered in order to realistically project climate change impacts on food supply (Parry *et al.*, 2004; Fischer *et al.*, 2005; Ewert *et al.*, 2005).

5.4.2.2 Review of impacts vs. incremental temperature change

The increasing number of regional and global simulation studies performed since the TAR makes it now possible to graph (Figure 5.2), with higher confidence than before, several aggregated relations (based on comparable modelling results) showing impacts of climate change on key crops against temperature signals–a proxy for both time and severity of climate change—as greenhouse gas concentrations increase over this century. Specifically, in temperate regions, moderate to medium local increases in temperature (1ºC to 3ºC), along with associated CO_2 increase and rainfall changes, can have small beneficial impacts on crops, including wheat, maize, and rice. Further warming has increasingly negative impacts (*medium to low confidence*). [Figure 5.2a, c, e]. In tropical regions, even moderate temperature increases are likely to have negative yield impacts for major cereals (1°C for wheat and maize, 2°C for rice) [Figure 5.2b, d, f]. For temperature increases more than 3°C, impacts are stressful to all crops and all regions (*medium to low confidence*) [Figure 5.2].

5.4.2.3 What has not been undertaken since the TAR – ongoing uncertainties

Several uncertainties remain unresolved since the TAR. In terms of experimentation: First, there is still a lack of knowledge of CO_2 and climate change response for many crops other than cereals, including many of importance to the rural poor, such as root crops, millet, etc, with few exceptions e.g., peanut, (Varaprasad *et al.*, 2003); mungbean (Dash *et al.*, 2002). Second, research on the combined effects of elevated CO_2 and climate change on pests, weeds and disease is still insufficient, though research networks have long been put into place (Scherm *et al.*, 2000); impacts of climate change-only on pest ranges and activity are being increasingly analyzed (e.g., Salinari *et al.*, 2006; Cocu *et al.*, 2005; Rafoss and Saethre, 2003; Bale *et al.*, 2002; Todd, 2002). Finally, the true strength of elevated CO_2 on crop yields at field to regional scales, as well as the CO_2 levels beyond which saturation may occur, remains largely unknown. Firstly, calls by the TAR to enhance crop model inter-comparison studies have remained unheeded; in fact, such activity has been performed with much less frequency after the TAR than before it. Yet it is important that uncertainties related to model implementation, including spatial-temporal resolution, be better understood, or integrated studies will remain dependent upon the particular crop model used. Secondly, it is still unclear how implementation of plot-level experimental data on CO_2 responses: a) compares across models; and: b) effectively represents field-scale responses – especially when simulations of several key limiting factors such as soil and water quality, pests weeds and disease, and the like, remain either unresolved or untested. Thirdly, the TAR had concluded that the economic-trade-technological assumptions used in many of the integrated assessment models were poorly tested against observed data. This remains the situation today; improvements in these models and more robust assumptions are needed in order to analyze scenarios of future agricultural systems with greater confidence.



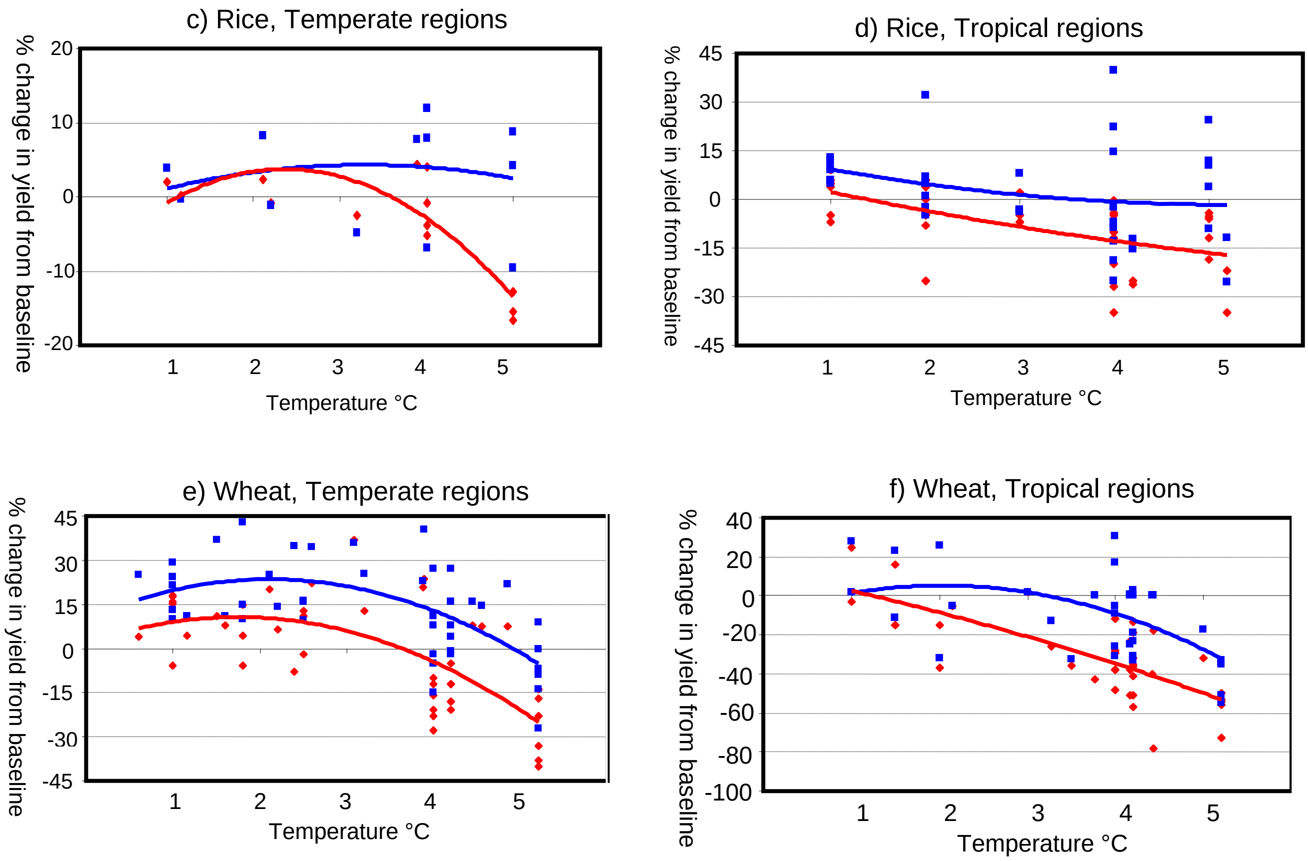


***Figure 5.2a-f:** Yield sensitivity to climate change for the major cereal crops, divided into temperate and tropical regions. Each graph aggregates results of several impact studies published after the TAR. Mean local temperature change is used in the abscissa as a generalized proxy indicating magnitude of climate impact in each study—this is by convention across WG II chapters. In each graph, polynomials have been derived to estimate general trends in yields versus temperature, both without adaptation (red lines) and with adaptation (blue lines). Although precipitation is not controlled, it is important to note that there were stronger statistical relationships of yield with precipitation and CO_2 changes, emphasizing the importance of these other factors in scenarios of future yield change.*

5.4.3 Pastures and livestock production

Pastures comprise both grassland and rangeland ecosystems. Grasslands are the dominant vegetation type in areas with low rainfall, such as the steppes of central Asia and the prairies of North America. Grasslands can also be found in areas with higher rainfall, such as north-western and central Europe, New Zealand, parts of North and South America and Australia. Rangelands are found on every continent, typically in regions where temperature and moisture restrictions limit other vegetation types; they include deserts (cold, hot and tundra), scrub, chaparral and savannas.

Pastures and livestock production systems are very diverse, occurring under most climates and ranging from extensive pastoral systems with free-ranging and grazing herbivores, to intensive systems based on forage and grain crops, where animals are mostly kept indoors. These systems are complex: production is the result of a mix of several plant and animal species that may be affected in different ways by climate factors. The TAR identified that the combination of increases in CO_2 concentration, in conjunction with changes in rainfall and temperature, were likely to have significant impacts on grasslands and rangelands, with production increases in humid temperate grasslands, but decreases in arid and semiarid regions.

5.4.3.1 New findings since TAR

***New Knowledge:** Plant community structure is modified by climate change and elevated CO_2.* Grasslands consisting of fast-growing, often short-lived species are sensitive to CO_2 and climate change and part of the impacts are related to the stability and resilience of plant communities (Mitchell and Csillag, 2001). Experiments support the concept of rapid changes in species composition and diversity under climate change. For instance, in a Mediterranean annual grassland, after 3 years, elevated CO_2 and nitrogen deposition each reduced plant diversity, whereas elevated precipitation increased it and warming had no significant effect (Zavaleta *et al.*, 2003). The effects of elevated CO_2, N deposition, and precipitation on total diversity were driven mainly by significant gains and losses of forb species. Elevated CO_2 influences plant species composition partly through changes in the pattern of seedling recruitment (Edwards *et al.*, 2001). For sown mixtures, the TAR indicated that elevated CO_2 increased legume development. This finding has been extended to temperate semi-natural grasslands using free air CO_2 enrichment (Ross *et al.*, Teyssonneyre *et al.*, 2002). Other factors such as low phosphorus availability and low herbage use (Teyssonneyre *et al.*, 2002) may, however, prevent this increase in legumes under high CO_2.

How to extrapolate these findings is still unclear. A recent modeling study of 1350 European plant species based on plant species distribution envelopes predicted that half of these species will become classified as 'vulnerable' or 'endangered' by the year 2080 due to rising temperature and changes in precipitation (Thuiller *et al.*, 2005) (see Chapter 4). Nevertheless, with managed grasslands, such model predictions have low confidence as they do not capture the complex interactions with factors such as grazing, cutting and fertilizer supply.

***New Knowledge:** Changes in forage quality and grazing behaviour are confirmed.* Animal requirements for crude proteins from pasture range from 7 to 8% of ingested dry-matter for animals at maintenance up to 24 % for the highest producing dairy cows. In conditions of very low N status, possible reductions in crude proteins under elevated CO_2 may put a system into a sub-maintenance level for animal performance. An increase in the legume content of swards may nevertheless compensate for the decline in the protein content of the non-fixing plant species (Allard *et al.*, 2003; Picon-Cochard *et al.*, 2004). C_4 grasses are a less nutritious food resource than C_3 grasses both in terms of reduced protein content and increased C/N ratios. Elevated carbon dioxide levels will likely reduce food quality to grazers both in terms of fine-scale (protein content, C/N ratio) and coarse-scale (C_3 versus C_4) changes (Ehleringer *et al.*, 2002). Large areas of upland Britain are already colonised by relatively unpalatable plant species such as bracken, matt grass and tor grass. At elevated CO_2 further changes may be expected in the dominance of these species, which could have detrimental effects on the nutritional value of extensive grasslands to grazing animals (Defra, 2000).

***New Knowledge:** Thermal stress reduces productivity, conception rates and is potentially life-threatening to livestock.* The TAR indicated the negative role of heat stress for productivity. Because ingestion of food/feed is directly related to heat production, any decline in feed intake and/or energy density of the diet will reduce the amount of heat that needs to be dissipated by the animal. Mader and Davis (2004) confirm that the onset of a thermal challenge often results in declines in physical activity with associated declines in eating and grazing (for ruminants and other herbivores) activity. New models of animal energetics and nutrition, (Parsons *et al.*, 2001) have shown that high temperatures in the tropics, puts a ceiling to dairy milk yield from feed intake at half to one third of the potential of the modern (Friesians) cow breeds. The energy deficit of this genotype will exceed that normally associated with the start of lactation, and decrease cow fertility, fitness and longevity (King *et al.*, 2005).

Increases in air temperature and/or humidity have the potential to 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. Amundson *et al*., (2005) reported declines in conception rates of cattle (*Bos taurus*) for temperatures above 23.4 ^{o}C and at high thermal heat index.

The impact on animal productivity due to increased variability in weather patterns will likely be far greater than effects associated with the average change in climatic conditions. Lack of prior conditioning to weather events may result in large losses in the domestic livestock industry. Economic losses from reduced cattle performance likely exceed those associated with cattle death losses by several-fold (Mader, 2003).

New Knowledge: *Increased climate variability and droughts may lead to livestock loss in arid pastoral systems*. Many of the world's rangelands are affected by ENSO events. The TAR identified that these events are likely to intensify with climate change with subsequent changes in vegetation and water availability (Gitay *et al*., 2001). In dry regions, there are risks that severe vegetation degeneration leads to a positive feedback between degradation of soils and vegetation and rainfall reduction with consequences in terms of loss of pastoral areas and of farmlands (Zheng *et al*., 2002).

A number of studies in Africa (see Table 5.2.) and in Mongolia (Batima, 2003) show a strong relationship between drought and animal death. Projected increased temperature, 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 (Medium confidence). With increased heat stress in the future, water requirements for livestock will also increase significantly when compared with current conditions so that overgrazing near watering points is likely to expand (Batima *et al*., 2005).

Table 5.2: *Impacts on grasslands of incremental temperature change.*

Local temperature change	Sub-sector	Region	Impact trends	Sign of impact	Scenario	Source
+0-2°C	Pastures and livestock	Temperate	Alleviation of cold limitation increasing productivity Increased heat stress for livestock	+ -	Simulation IS92a	Riedo *et al*., 2001 Turpenny *et al.,* 2001
		Semi-arid and Mediterranean	No increase in net primary productivity	0	EXP	Dukes *et al*., 2005 Shaw *et al*., 2002
		Tropical	Positive (irrigated conditions)	+	EXP	Newman *et al.,* 2001 Lilley *et al*., 20011
+3°C	Pastures and livestock	Temperate	Neutral to small positive effect (depending on GMT)	0 to +	Simulation	Riedo *et al*., 2001 Parsons, 2001
		Temperate	Negative on swine and confined cattle	-	HadCM CGCM	Frank and Dugas, 2001
		Semi-arid and Mediterranean	Productivity decline Reduction in ewe weight and pasture growth Increased animal heat stress	- -	EXP HadCM3 A2 and B2	Shaw *et al.* 2005 Batima *et al*., 2005 Howden *et al.,* 1999
		Tropical	No effect (no rainfall change assumed) Increased animal heat stress	- to 0 -	EXP	Newman *et al.,* 2001 Volder *et al*., 2004

5.4.3.2 Impacts of incremental temperature change

A survey of experimental data worldwide suggested that a mild warming generally increases grassland productivity, with the strongest positive responses at high latitudes (Rustad *et al.*, 2001). Productivity and plant species composition in rangelands are highly correlated with precipitation (Knapp and Smith, 2001) and recent findings from WG I (see Figure 5.1) show projected declines in rainfall in some major grassland and rangeland areas (e.g. South America, South and North Africa, Western Asia, Australia and Southern Europe). Elevated CO_2 can reduce soil water depletion in different native and semi-native temperate and Mediterranean grassland (Morgan *et al.*, 2004). However, increased variability in rainfall may create more severe soil moisture limitation and reduced productivity (Laporte *et al.*, 2002; Fay *et al.*, 2003, Luscher *et al.*, 2005). Other impacts occur directly on livestock through the increase in the thermal heat load (see 5.4.3.1).

Table 5.2 summarises the impacts on grasslands for different temperature changes. Warming up to 2°C suggests positive impacts on pasture and livestock productivity in humid temperate regions. By contrast, negative impacts are predicted in arid and semiarid regions. Changes in rainfall patterns, increased climate variability and extreme events, in addition to changes in mean temperature conditions, may suppress positive effects and exacerbate negative impacts in all regions.

5.4.4 Industrial crops and biofuels

Minimal new knowledge of climate change impacts on industrial crops and biofuels was developed since the TAR. Impacts of climate change and elevated CO_2 on perennial industrial crops will likely be magnified with respect to those on annual crops, as both damages (for example, temperature stresses, pest outbreaks, increased damage from climate extremes) and benefits (e.g., extension of latitudinal optimal growing ranges) may accumulate through several years (Rajagopal *et al.*, 2002). For example, the cyclones that struck several states of India in 1952, 1955, 1996 and 1998 have destroyed so many coconut palms that it will take years before the level of production can be brought back to that of the pre-cyclone period (Dash *et al.*, 2002). The enhanced progression of phenological stages of the grapevines due to increased temperatures would lead to early ripening. This will impact on the grapevines in either positive or negative ways depending on the present climate of the region. A climatic warming will likely expand the suitable wine areas northwards and eastwards in Europe (Harrison *et al.*, 2000).

The large increase in cotton yields due to climate change was well established in 1990s and hence there have been few studies on this aspect since the TAR. Reddy *et al.* (2002), however, demonstrated that large increases in cotton due to enhanced CO_2 were eliminated when all projected climatic changes were included and additional irrigation would be needed to satisfy the increased water demand of the crop. Literature still does not exist on the probable impacts of climate change on other fibre crops such as jute and kenaf.

Biofuel crops, increasingly an important source of energy, are being assessed for their critical role in adaptation to climatic change and mitigation of carbon emissions (discussed in WGIII). Impacts of climate change on typical liquid biofuel crops such as corn and sorghum, and wood (solid biofuel) have been discussed earlier in this chapter. Recent studies indicate that the yield of sugar beet, another important biofuel crop, may increase in Europe by 3-5 t/ha by 2080 in silt and loamy soils (Richter *et al.*, 2006). Studies with other biofuel crops such as switchgrass (*Panicum virgatum L.*), a perennial warm season, C_4 crop have shown yield increases with climate change similar to grain crops (Brown *et al.*, 2000). Although there is no information on the impact of climate change on non-food, tropical biofuel crops such as Jatropha and Pongamia, it is likely that their response would be similar to other crops of the region.

5.4.5 Key future impacts on Forestry

Forests cover almost 4B ha or 30% of land; 3.4B m3 of wood were removed in 2004 from this area, of which 60% is industrial roundwood and the rest fuelwood (FAO 2005). Of the forest area, in 2005 only 3% were productive forest plantations, but this share is rapidly increasing by 2.5 mil. ha annually and supplies over 35% of global roundwood, (FAO, 2000). This section focuses on commercial forestry (versus ecosystem services of forests in Chapter 4), including regional, national and global timber supply and demand, and associated changes in land-use, accessibility for harvesting, and overall economic impacts.

5.4.5.1 New findings since the TAR

Confirmation of TAR: *Modeling studies predict increased global timber production.* The new models generally predict increasing global forest productivity under climate change, especially when positive effects of elevated CO2 concentration are taken into consideration (Alig *et al.*, 2002; Sohngen *et al.*, 2001; Sohngen, 2005; Solberg, 2003b; Ireland, 2004). Changing timber supply will affect the market and could impact supply for other uses, e.g., for biomass energy. Simulations with yield models show that climate change can increase global timber production through location changes of forests and higher growth rates. Sohngen *et al.* (2001, 2005) projected a moderate increase of timber yield due to both rising NPP and poleward shift of the most productive species due to climate change. Global economic impact assessments predict overall demand for timber production to increase only modestly (see 5.3.2.2) with a moderate increase or decrease of wood prices in the future in the order of up to +/-20% (Perez-Garcia *et al.*, 2002; Nabuurs *et al.*, 2002; Solberg, 2003a; Ireland, 2004; Sohngen *et al.*, 2001 Sohngen, 2005), with benefits of higher production mainly going to consumers. For the US, Alig *et al.*, 2002) computed that the net impact of climate change on the forestry sector may be small. Shugart *et al.*, 2003 concluded that the United States timber markets have low susceptibility to climate change, because of the large stock of existing forests, technological change in the timber industry, and the ability to adapt. These and other simulation studies are summarized in the Table 5.3.

New Knowledge: *Increased regional variability; change in non-timber forest products.* Although models suggest that global timber productivity will likely increase with climate change, regional production may exhibit large variability, as discussed for crops. Mendelsohn, (2003), analyzing production in California, projected that at first (2020s), climate change increases harvests by stimulating growth in the standing forest. In the long run (up to 2100), these productivity gains were offset by reductions in productive area for softwoods growth. Climate change may also substantially impact other services, such as seeds, nuts, hunting, resins, plants used in pharmaceutical and botanical medicine, and in the cosmetics industry, but little if any analysis is done in this area.

New Knowledge: *CO_2 enrichment effects may be overestimated in models; models need improvement.* New studies suggest that direct CO_2 effects on tree growth should be revised to towards lower values than previously assumed in forest growth models. For example, in a free-air CO2 enrichment experiment Korner (2005) found little overall stimulation in stem growth of 32-35 m trees after four years of exposure to CO_2 levels elevated to 530 ppm. Indeed, the initial increase in growth increments may be limited by competition, disturbance, air pollutants, nutrient limitations and other factors (Karonsky, 2003). As a contrast, models often presume large fertilization effects - e.g., Sohngen *et al.* (2001) used in their projections 35% NPP increase under 2xCO2 scenario. Still, regardless of the isolated effect of CO2 enrichment, recent research (Boisvenue and Running, 2006) suggests that climate change impacts on forest productivity since the middle of the 20th century have been overwhelmingly positive.

In spite of gains in forest modelling noted above, model limitations persist. Most of the major models don't include key ecological processes. Further development of Dynamic Global Vegetation Models (DGVMs), spatially explicit and dynamic transient models may allow better predictions of climate induced vegetative changes (Cramer *et al.*, 2001;Moorcroft, 2003;Peng, 2000B; Brovkin, 2002; Sitch *et al.*, 2003; Bachelet *et al.*, 2001), by simulating the composition of deciduous/evergreen trees, forest biomass, production, water and nutrient cycling, as well as fire effects. There are still inconsistencies however between the models used by ecologists to estimate the effects of climate change on forest production and composition, and the models used by foresters to predict forest yield. Future development of the models that integrate both the NPP and forestry yield approaches (Peng *et al.*, 2002; Nabuurs *et al.*, 2002) will significantly improve the predictions.

Table 5.3: *Simulated climate change impact on forestry: results of some global and regional models.*

Study/location	Scenario	Impact
Sohngen *et al.*, 2001 Global	UIUC, Hamburg T-106 for 340 (current) and 550 (2060) ppmv CO2; no change after 2060	Near-term growth of timber production by 5%, especially in low latitudes—gradually rising by 30% in long-term. Long-term growth of timber production by 34-41% for North America, 4-24% for Europe, 44-66% for FSU, 27-32% for China, 10-29% for Oceania, 23-42% for South America, 29-47% for India, 11-28% for Asia-Pacific, and 21-37% for Africa. Moderate increase in global timber prices from current \$75 to \$135 per m^3 by year 2100 without climate change; with climate change: \$110±\$5 per m^3.
Solberg, 2003b Global	Baseline, 20% growth increase; 40% growth increase (climate change assumed one of several potential growth factors)	20% scenario: 7-9% roundwood price drop in Europe. 40% scenario: 13-17% roundwood price drop in Europe. Increased roundwood harvest in Western Europe, decreased in Eastern Europe, incl. Russia. Increased profits of forest industry and forest owners
Perez-Garcia *et al.*, 2002 Global	MIT GCM and MIT EPPA emission scenarios (RRR,HHL,LLH) . E.g., RRR is similar to IS92a.	Mid-term increase of harvest by 1.5 – 2.7% and a small price drop with an increase in welfare to producers and consumers. Highest harvest increase in the US West (+2 - +11%), New Zealand (10-12%), and Chile (+10 - +13%); lowest in Western Europe (-3 - +1%) and Canada (-3 - -1%). Price drop is greatest in West Europe and Scandinavia.
Lee and Lyon, 2004 Global	ECHAM-3 under 2xCO2	Increase of the industrial timber harvest in 2080s by 65% (normal demand) and 150% (high demand). In the absence of climate change, increase by 25% and 56%, correspondingly.
Nabuurs *et al.*, 2002 Europe .	HadCM2 under IS92a	Near-term 18% extra increase in annual stemwood increment, slowing down later.
Schroeter, 2004 Europe	IPCC A1f, A2, B1, B2.	Several management scenarios considered. Management explains 60-80% of stock change between 2000 and 2100, climate explains 10-30%, LUC explains 5-22%. Increased forest growth except for A1f; Increased stocks excl. in A1f; demand satisfied excl. A1f, A2.
Sohngen, 2005 Global, USA	UIUC, Hamburg T-106 for 340 and 550 (2060) ppmv CO2; no change after 2060	Increased global productivity, reduction in prices. Gain to consumers; producers lose. Reductions in production in North America and Russia; increased production in South America and Oceania.

Lexer *et al.*, 2002 Austria	A: IPCC IS92a; B: T +2C; C: T +2C and P -15% in summer.	A: Low climate change impact (integral index based on biomass, composition, etc.) at 67% of sites (A), 18% (B), and 15.5% (C) Shift to broadleaved species.
Rathgeber *et al.*, 2003 France	ALCM under 2xCO2 scenario	Production gain by 17-24% (without CO2 fertilization), 107-141% (with fertilization).
Alig *et al.*, 2002 USA	CGCM1, HadMC2 under IS92a	Increase in timber inventory by 12% (mid-term); 24% (long-term). Small increase in harvest (few percent).
Joyce *et al.*, 2001 USA	CGCM1, HadMC2 under IS92a	Increase in forest inventory. Growth in price for standing timber by 35 – 45%, following by decreasing consumer costs and a decrease in forest total welfare. Major shift in species and an increase in burnt area by 25-50%. Decrease in consumer costs.

5.4.5.2 Additional factors not included in the models contribute uncertainty

Fire, insects and extreme events are not well modeled. Both forest composition and production are shaped by fire frequency, size, intensity, and seasonality. There is evidence of both regional increase and decrease in fire activity (Goldammer and Mutch, 2001; Mouillot and Field, ; Podur, 2002; Bergeron *et al.*, 2004; Girardin, 2004). Climate change will interact with fuel type, ignition source, topography, in determining future damage risks to the forest industry, especially for paper and pulp operations; fire hazards will also pose health threats (Chapter 8.2) and affect landscape recreational value. There is high uncertainty associated with most studies of climate change and forest fires (Lemmen and Warren, 2004; Shugart *et al.*, 2003). Current modelling studies suggest that increased temperatures and longer growing seasons will elevate fire risk in connection with increased aridity (Flannigan, 2005; Williams *et al.*, 2001). For example, Crozier *et al.*, 2002) indicated the possibility of a 10% increase in the seasonal severity of fire hazard over much of the United States under changed climate, while Flannigan, 2005 projected as much as 74-118% increase of the area burned in Canada by the end of the 21st century under a 3xCO_2 scenario. However, the effects of climate induced wildfires on timber production could be modest since much of the fire is expected in inaccessible boreal forest regions.

For many forest types, insect outbreaks are major sources of natural disturbance. The effects vary from defoliation and growth loss, to timber damage, to massive forest diebacks; it is very likely that these natural disturbances will be altered by climate change and will have an impact on forestry (Alig and al., 2004). Warmer temperatures have already enhanced the opportunities for insect spread across the landscape (Crozier *et al.*, 2002; Carroll, 2004). Climate change can shift the current boundaries of insect species and modify tree physiology and tree defence mechanisms. Modelling of climate change impacts on insect outbreaks remains limited.

The effects of climate extremes on commercial forestry could include reduced access to forestland, increased costs for road and facility maintenance, direct damage to trees by wind, snow, frosts, or ice; indirect damage from higher risks of wildfires and insect outbreaks, effects of wetter winters and early thaws on logging, etc. Higher direct and indirect risks could affect timber supplies, market prices, and cost of insurance. (DeWalle *et al.*, 2003; Fleming, 2002). Globally, early model predictions mentioned in the SAR suggested extensive forest dieback and composition change, however such affects may be mitigated by humans (Shugart *et al.*, 2003); changes in forest composition will likely occur gradually (Hanson and Weltzin, 2000).

Interaction between multiple disturbances is very important for understanding climate change impact on forestry. Wind events can damage trees through branch breaking, crown loss, trunk breakage, or complete stand destruction, especially due to faster build-up of growing stocks in a warmer climate. This damage can be further aggravated by increased damage from insect outbreaks and wildfires (Nabuurs *et al.*, 2002). Severe drought increases mortality and is often combined with insect and pathogens damage and wildfires. For example, a positive feedback between deforestation, forest fragmentation, wildfire, and increased frequency of droughts appear to exist in the Amazon basin, so that warmer and drier regional climate may trigger massive deforestation (Laurence, Williamson, 2001; Nepstad *et al.*, 2004). Only few if any models can simulate these effects (e.g., Blennow and Sallnas, 2004).

5.4.5.3 Social and economic impacts

Climate change impacts on forestry will translate into social and economic impacts through the relocation of forest economic activity. Distributional affects would involve businesses, landowners, workers, consumers, governments and tourism, with some groups and regions benefiting while others experience losses. Net benefits would accrue to regions experiencing increased forest production while regions with declining activity will likely experiences net losses. If wood prices decline as most models predict, consumers would experience net benefits, while producers experience net losses. Overall economic benefits would exceed losses. Although forest-based communities in the developing would (e.g., 60 million highly forest-dependent people living in the rainforests – FAO, 2004b) are likely to have modest impact on global wood production, they may be especially vulnerable due to limited adaptability in rural, resource dependent communities to respond to risk in a proactive manner (Davidson *et al.*, 2003; Lawrence, 2003).

5.4.6 Capture fisheries and aquaculture: marine and inland waters

World capture production of fish, crustaceans and molluscs in 2003 was more than twice the quantity of aquaculture (Table 5.4), but capture production decreased by nearly 5% since 1997, whereas aquaculture increased by nearly 50%. By 2030 capture production and aquaculture are projected to be closer to equality (93 M tons and 83 M tons respectively, (F.A.O., 2002). Aquaculture resembles terrestrial animal husbandry more than it does capture fisheries and therefore shares many of the vulnerabilities and adaptations to climate change with that sector. Similarities between aquaculture and terrestrial animal husbandry include ownership, control of inputs, diseases and predators and use of land and water.

Table 5.4: *World Fisheries Production in 2003 (source: FAO, Yearbook of Fisheries Statistics http://www.fao.org/fi/statist/statist.asp)*

World production in M tons		Inland	Marine
Capture production	Fish, crustaceans, molluscs etc.	8.9	81.3
Aquaculture production	Fish, crustaceans, molluscs etc.	25.2	17.1
	Aquatic plants	0.0	12.5

Some aquaculture, particularly of plants and molluscs, depends on naturally occurring nutrients and production, but rearing of fish and crustacea usually requires addition of suitable food, obtained mainly from capture fisheries. Capture fisheries depend on the productivity of the natural ecosystems on which they are based and are therefore vulnerable to changes in primary production and how this production is transferred through the aquatic food chain. (Climate induced change in production in natural aquatic ecosystems is dealt with in chapter 4).

5.4.6.1 TAR conclusions remain valid

The principal conclusions concerning aquaculture and fisheries set out in the TAR (see section 5.1.3) remain valid and important. The negative impacts of climate change which the TAR identified, particularly on aquaculture and freshwater fisheries, include (i) stress due to increased temperature and oxygen demand and decreased pH (ii) uncertain future water supply (iii) extreme weather events (iv) increased frequency of disease and toxic events (v) sea-level rise and conflict of interest with coastal defence needs (vi) uncertain future supply of fishmeal and oils from capture fisheries. Positive impacts include (i) increased growth rates and food conversion efficiencies (ii) increased length of growing season (iii) range expansion (iv) use of new areas due to decrease in ice cover.

Information which has appeared since the TAR from experimental, observational and modelling studies supports these conclusions and provides more detail, especially concerning regional effects. However, for aquatic systems we still lack the kind of experimental data and models which are used to predict agricultural crop yields under different climate scenarios.
One of the few experimental studies showed positive effects on appetite, growth, protein synthesis and oxygen consumption of a 2^oC increase in winter, but negative effects of the same temperature increase in summer, for Rainbow trout (*Oncorhyncus mykiss*). Thus rising temperature may cause seasonal increases in growth, but also risks to fish populations living towards the upper end of their thermal tolerance zone. Increasing temperature interacts with other global changes, including declining pH and increasing nitrogen and ammonia to increase metabolic costs. The consequences of these interactions is speculative and complex (Morgan *et al.*, 2001).

Fisheries and aquaculture are subject to multiple stresses due to human activity, as Box 5.3 on the fisheries of the Mekong illustrates.

Box 5.3: Climate change and the fisheries of the lower Mekong

Fisheries are central to lives of the people, particularly the rural poor, who live in the lower Mekong countries. Two thirds of the basin's 60 million people are in some way active in fisheries, which represent about 10% of the GDP of Cambodia and Lao PDR. There are approximately 1000 species of fish commonly found in the river, with many more marine vagrants, making it one of the most prolific and diverse faunas in the world (MRC, 2003). Recent estimates of the annual catch from capture fisheries alone exceed 2.5 million tonnes (Hortle and Bush, 2003), with the delta contributing over 30% of this.

Direct effects of climate will occur due to changing patterns of precipitation, snow melt and rising sea level which will affect hydrology and water quality. Indirect effects will result from changing vegetation patterns that may alter the food chain and increase soil erosion. It is likely that human impacts on the fisheries (caused by population growth, flood mitigation, increased water abstractions, changes in land use and overfishing) will be greater than the effects of climate, but the pressures are strongly interrelated.

An analysis of the impact of climate change scenarios on the flow of the Mekong (Hoanh *et al.*, 2004) estimated increased maximum monthly flows of 35 – 41% in the basin and 16 – 19% in the delta (lower value is for years 2010 – 38 and higher value for years 2070 – 99, compared with 1961 - 90 levels). Minimum monthly flows were estimated to fall by 17 – 24% in the basin and 26 – 29% in the delta. Increased flooding would be positive for fisheries yields, but a reduction in dry season habitat may reduce recruitment of some species. However, planned water management interventions, primarily dams, are expected to have opposite effects on hydrology, namely marginally decreasing wet season flows and considerably increasing dry season flows (Anon, 2004).

Models indicate that even modest sea level rises of 20cm would cause contour lines of water levels in the Mekong delta to shift 25 km towards the sea during the flood season and salt water to move further upstream (although confined within canals) during the dry season (Wassmann *et al.*, 2004). Inland movement of salt water would significantly alter the species composition of fisheries, but may not be detrimental for overall fisheries yields.

5.4.6.2 New information on trends in distribution, production and disease

Direct effects of increasing temperature on marine and freshwater ecosystems are already evident, with rapid poleward shifts in regions, such as the NE Atlantic, where temperature change has been rapid – see Chapter 1, on changes in plankton, fish distribution and production in the NE Atlantic. Further changes in distribution and production are expected due to continuing warming and freshening of the Arctic (ACIA, 2005; Drinkwater, 2005). Local extinctions are occurring at the edges of current ranges, particularly in freshwater and diadromous species e.g. salmon (Friedland *et al.*, 2003) and sturgeon (Reynolds *et al.*, 2005).

Changes in primary production and transfer through the food chain due to climate will have a key impact on fisheries. Such changes may be either positive or negative and the aggregate impact at global level is unknown. There is evidence from the Pacific and the Atlantic that nutrient supply to the upper productive layer of the ocean is declining due to reduced meridional overturning circulation and upwelling (McPhaden and Zhang, 2002); (Curry and Mauritzen, 2005) and changes in windborne nutrients. This has resulted in reduction in primary production (Gregg *et al.*, 2003), but there is considerable regional variability (Lehodey *et al.*, 2003). The decline in pelagic fish catches in Lake Tanganyika since the late 1970's has been ascribed to climate induced increase in vertical stability of the water column, resulting in reduced availability of nutrients (O'Reilly *et al.*, 2004).

Coupled simulations used six different models to determine the ocean biological response to climate warming between the beginning of the industrial evolution and 2050 (Sarmiento *et al.*, 2005). They show global increases in primary production of 0.7 to 8.1%, but with large regional differences, which are described in Chapter 4. Palaeological evidence and simulation modelling show North Atlantic plankton biomass declining by 50% over a long time scale during periods of reduced meridional overturning circulation (Schmittner, 2005). Such studies are speculative, but an essential step in gaining better understanding. The observations and model evidence cited above provide grounds for concern that aquatic production, including fisheries production, will suffer regional and possibly global decline and that this has already begun.

Climate change has been implicated in mass mortalities of many aquatic species, including plants, fish, corals and mammals, but lack of standard epidemiological data and information on pathogens generally makes it difficult to attribute causes (Harvell *et al.*, 1999). An exception is the northward spread of two protozoan parasites (*Perkinsus marinus* and *Haplosporidium nelsoni*) from the Gulf of Mexico to Delaware Bay and further north, where they have caused mass mortalities of Eastern oysters (*Crassostrea virginica*). Winter temperatures consistently lower than 3°C limit the development of the MSX disease caused by *Perkinsus* (Hofmann *et al.*, 2001) and the poleward spread of this and other pathogens can be expected to continue as such winter temperatures become rarer.

Factoring in the number of fisher folks, nutritional dependency on fish products and poverty levels, a recent modelling study predicts that, for the fisheries sector, climate change will have the greatest impact on the national economies of Central and Northern Asian countries, the Western Sahel, coastal tropical regions of South America (Allison *et al.*, 2005) as well as some small and medium-sized island states (Aaheim and Sygna, 2000).

Indirect economic impacts of climate change will depend on the extent to which the local economies are able to adapt to new conditions in terms of labour and capital mobility. Change in natural fisheries production is often compounded by decreased harvesting capacity and reduced physical access to markets linked to the effects of extreme weather events on coastal and inland fishing communities (Allison *et al.*, 2005).

5.4.6.3 Impacts of decadal variability and extremes

Most of the large global marine capture fisheries are affected by regional climate variability. Recruitment of the two tropical species of tuna (skipjack and yellowfin) and the subtropical albacore (*Thunnus alalunga*) in the Pacific is related to regimes in the major climate indices, ENSO and the Pacific Decadal Oscillation (Lehodey *et al.*, 2003). Large-scale distribution of skipjack tuna in the western equatorial Pacific warm pool can also be predicted from a model linked to changes in ENSO (Lehodey, 2001). ENSO events, which are defined by the appearance and persistence of anomalously warm water in the coastal and equatorial ocean off Peru and Ecuador for periods of 6 to 18 months, have adverse effects on Peruvian anchovy production in the eastern Pacific (Jacobson *et al.*, 2001). However, longer term, decadal anomalies appear to have greater long-term consequences for the food-web than the short periods of nutrient depletion during ENSO events (Barber *et al.*, 2001). Models relating interannual variability, decadal (regional) variability and global climate change must be improved in order to make better use of information on climate change in planning management adaptations.

North Pacific ecosystems are characterised by “regimes shifts” - fairly abrupt changes in both physics and biology which then persist for periods of a decade. These changes have major consequences for the productivity and species composition of fisheries resources in the region (King, 2005). ENSO influences the regional climate of the North Pacific quite strongly and it should therefore be possible to extend the predictability of the system, which for ENSO is currently about 9 months.

Major changes in Atlantic ecosystems, from plankton to fish and birds, can also be related to regional climate indicators, in particular the NAO (Drinkwater *et al.*, 2003 - see also Chapter 1 on NE Atlantic plankton, fish distribution and production). Surplus production of fish stocks, such as cod in European waters, has been adversely affected by the positive trend in the NAO since the 1960’s and the recruitment is more sensitive to climate variability when variability when spawning biomass and population structure are reduced (Brander, 2005). In order to reduce sensitivity to climate, stocks must be maintained at higher levels.

Climate related reductions in surplus production cause fish stocks to decline at levels of fishing which had previously been sustainable, therefore the effects of climate must be correctly attributed and taken into account in fisheries management.

Box 5.4: Impact of coral mortality on reef fisheries

Coral reefs and their fisheries are subject to many stresses in addition to climate change (see chapter 4). So far, events such as the 1998 mass coral bleaching in the Indian Ocean have not provided evidence of negative short-term bio-economic impacts for coastal reef fisheries (Grandcourt and Cesar, 2003; Spalding and Jarvis, 2002). In the longer term, there may be serious consequences for fisheries production resulting from loss of coral communities, reef habitat and altered architecture. These are currently being investigated.

5.4.7 Rural livelihoods: subsistence and smallholder agriculture

The impacts of climate change on subsistence and smallholder agriculture, pastoralism and artisanal fisheries can be considered in terms of compound impacts specific to location and livelihood systems in different ecosystems and regions of the world, all within a very specific context of high vulnerability and limited capacity for adaptation (Adger *et al.*, 2003). It is difficult to ascribe levels of confidence to these predicted compound impacts. A conceptual model is shown in Figure 5.3. These livelihood systems are typically complex; they produce a number of crop and livestock species, between which there are interactions – for example, intercropping practices or the use of draught animal power for cultivation, and potential substitutions such as alternative crops. Many smallholder livelihoods will also include use of wild resources, and non-agricultural strategies, such as use of remittances. The interactions between all these elements will be different under "normal" conditions and when coping with crises such as drought.

Impacts upon these systems will include:

- The direct impacts of changes in temperature, CO_2 and precipitation on yields of specific food and cash crops, and productivity of livestock and fisheries systems, as discussed in Sections 5.4.1 to 5.4.6 above. These will include both impacts of changing means and increased frequency of extreme events, with the latter being more important in the short-term (to 2020). Positive and negative impacts on different crops may occur in the same farming system. Agrawala *et al.* (2003) suggest that impacts on maize, the main food crop, will be strongly negative for the Tanzanian smallholder, while impacts on coffee and cotton, significant cash crops, may be positive.
- Other physical impacts of climate change important to smallholders are: i) the effects of decreasing snowcap on major smallholder irrigation systems, particularly in the Indo-Gangetic plain, ii) the effects of sea level-rise on coastal areas, iii) increased frequency of landfall tropical storms (Adger, 1999), iv) effects on soils, and v) other forms of environmental impact still being identified, such as increased forest fire risk (Agrawala *et al.*, 2003 for the Mount Kilimanjaro ecosystem) and remobilization of dunes (Thomas *et al.*, 2005 for semi-arid Southern Africa);
- impacts on human health such as increased malaria risk (see Chapter 8) and thus ability to provide labour for agriculture, and on non-farm rural economic activities, such as tourism (Chapter 7);
- non-climate stressors as listed in 5.2.2 above.

For climate change impacts on the three major cereal crops most often grown by smallholders, we refer to Figure 5.2 (a-f) and discussion in 5.4.2 and 5.5.1. In section 5.4.1 above we discuss the various negative impacts of increases in climate variability and frequency of extreme events on yields. Projected impacts on world regions, some of which are disaggregated to smallholder and subsistence farmers or similar categories, are reviewed in the respective regional chapters. An important study is that of Jones and Thornton (2003) finding that aggregate yields of smallholder rainfed maize in Africa and Latin America are likely to show a decrease of almost 10% by 2055, but that these results hide enormous variability (see also Fischer *et al.*, 2002) and give cause for concern, especially in some areas of subsistence agriculture.

The location of a large body of smallholder and subsistence farming households in the dryland tropics therefore gives rise to especial concern over temperature-induced decline in crop yields, and increasing frequency and severity of drought (see Summary for Policy Makers, Report of Working Group I). These will lead to the following generalizations (*low confidence*):

- increased likelihood of crop failure
- increased mortality of livestock and/or forced sales of livestock at disadvantageous prices

- livelihood impacts including sale of other assets, indebtedness, out-migration and dependency on food relief
- eventual impacts on human development indicators such as health and education.

Impacts of climate change will also be experienced in combination with impacts of globalisation (O'Brien and Leichenko, 2000). There is a similar risk of interactions with the impacts of HIV/AIDS (Gommes *et al.*, 2004, see also chapter 8).

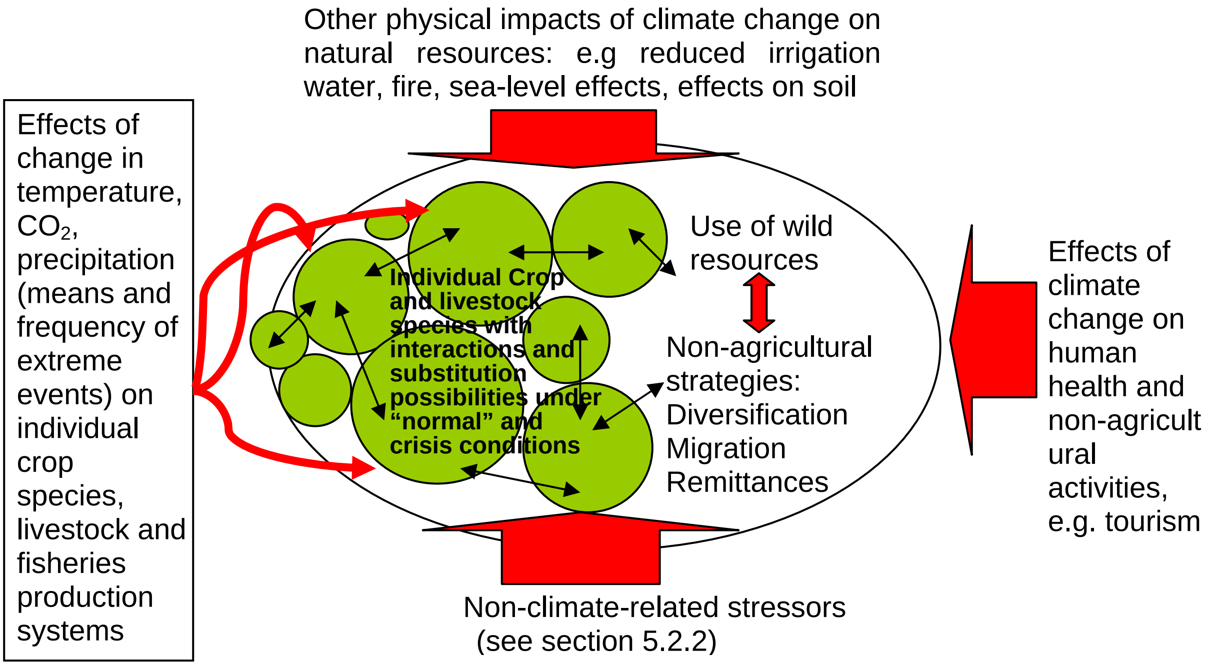


Figure 5.3: *Conceptual model of climate change impacts on small holder and subsistence agriculture*

Understanding the interactions between these different forms of climate change impact, and the adaptations these will bring about, calls for modelling work. The multi-agent modelling of Bharwani *et al.* (2005) is one possible approach. Also important will be increased empirical research on how current strategies to cope with extreme events foster or constrain longer-term adaptation. Knowledge of crop responses to climate change also needs to be extended to more crops of interest to smallholders.

5.5. Adaptations: Options and Capacities

Adaptation is used here to mean both the actions of adjusting practices, processes and capital in response to the actuality or threat of climate change as well as changes in the decision environment such as social and institutional structures and altered technical options that can affect the potential or capacity for these actions to be realised (Chapter 17). We divide discussions on adaptation into two categories: *autonomous*, which is the ongoing implementation of existing knowledge and technology in response to the changes in climate experienced, and *planned*, which increases adaptive capacity by mobilizing institutions and policies to establish or strengthen conditions favourable for effective adaptation activities and invests in new technologies and infrastructure.

The TAR noted agriculture has historically shown high levels of adaptability to climate variations and that whilst there were many studies of climate change impacts, there were relatively few that had comparisons with and without adaptation. Generally the adaptations assessed were most effective in mid-latitudes and least effective in low-latitude developing regions with poor resource endowments and where ability of farmers to respond and adapt was low. There was limited evaluation of either the costs of adaptation or of the environmental and natural resource consequences of adaptation. Generally, adaptation studies have focussed on situations where climate changes are expected to have net negative consequences: there is a general expectation that if climate improves, then market forces and the general availability of suitable technological options will result in effective change to new, more profitable or resilient systems (e.g. Parsons, 2001)

5.5.1 Autonomous adaptations

Many of the autonomous adaptation options identified before and since the TAR are largely extensions or intensifications of existing risk management or production enhancement activities. For cropping systems there are many potential ways to alter management to deal with projected climatic and atmospheric changes (Alexandrov, 2002; Adams *et al.*, 2003; Tubiello *et al.*, 2002; Easterling *et al.*, 2003; Howden, 2003a; Howden and Jones, 2004; Aggarwal and Mall, 2003; Butt *et al.*, 2005). These adaptations include:

- altering inputs such as varieties/species to those with more appropriate thermal time and vernalisation requirements and/or with increased resistance to heat shock and drought, altering fertiliser rates to maintain grain or fruit quality consistent with the prevailing climate, altering amounts and timing of irrigation
- wider use of technologies to 'harvest' water, conserve soil moisture (e.g. crop residue retention) and to use water more effectively
- altering the timing or location of cropping activities
- diversifying income including through altering the integration with other farming activities such as livestock raising
- improving the effectiveness of pest, disease and weed management practices through wider use of integrated pest management, development and use of varieties and species resistant to pests and diseases and maintaining or improving quarantine capabilities, sentinel monitoring programs
- using seasonal climate forecasting to reduce production risk.

If widely adopted, these autonomous adaptations singly or in combination have substantial potential to offset negative climate change impacts and take advantage of positive ones. For example, in Modena, Italy, simple, currently practicable adaptations of varieties and planting times to avoid drought and heat stress during the hotter and drier summer months predicted under climate change altered significant negative impacts on sorghum (-48 to -58%) to neutral to marginally positive ones (0 to +12%; 2002). We have synthesised results from many crop adaptation studies for wheat, rice and maize (Fig. 5.2). The benefits of adaptation vary with crops and across regions and temperature changes, however, on average, they provide approximately a 10% yield benefit. Another way of viewing this is that these adaptations translate to damage avoidance in grain yields of rice, wheat and maize crops caused by a temperature increase of up to 1.5 to 3^{o}C in both temperate and tropical regions. The benefits of autonomous adaptations tend to level off with increasing temperature changes (Howden and Crimp, 2005).

While autonomous adaptations such as the above have the potential for considerable damage avoidance from problematic climate change, there has been little evaluation of how effective and widely adopted these adaptations may actually be given 1) the complex nature of farm decision-making in which there are many non-climatic issues to manage, 2) the likely diversity of responses within and between regions in part due to possible differences in climate changes, 3) the difficulties that might arise if climate changes are non-linear or increase climate variability, 4) time lags in responses and 5) the possible interactions between different adaptation options and economic, institutional and cultural barriers to change. For example, the realisable adaptive capacity of poor subsistence farming/herding communities, is generally considered to be very low (Leary *et al.*, 2006).

These caveats apply to the livestock, forestry and fisheries sectors as well.

Adaptations in field-based livestock include additional care to continuously matching stocking rates with pasture production, altered rotation of pastures, modification of times of grazing, alteration of forage and animal species/breeds, altered integration within mixed livestock/crop systems including the use adapted forage crops, re-assessing fertilizer applications and the use of supplementary feeds and concentrates (Daepp *et al.*, 2001; Hodden and Brereton, 2002; Adger *et al.*, 2003; Maltitz, 2005; Batima *et al.*, 2005; Wehbe, 2005; Balgis). It is important to note however, that there are often limitations to these adaptations. For example, more heat tolerant livestock breeds often have lower levels of productivity. In intensive livestock industries, in cold climates there may be reduced need for winter housing and for feed concentrates but in warmer climates there could be increased need for management and infrastructure to ameliorate heat stress-related reductions in productivity, fertility and increased mortality (Gaughan *et al.*, 2002).

A large number of autonomous adaptation strategies, have been suggested for planted forests including changes in management intensity, hardwood/softwood species mix, timber growth and harvesting patterns within and between regions, rotation periods, salvaging dead timber, shifting to species or areas more productive under the new climatic conditions, landscape planning to minimize fire and insect damage and provide connectivity, adjusting to altered wood size and quality and adjusting fire management systems (Alig *et al.*, 2002; Spittlehouse and Stewart, 2003; Spittlehouse, 2005; Natural Resources Canada, 2004; Sohngen *et al.*, 2001; Weih, 2004). Adaptation strategies to control insect damage can include prescribed burning for reducing forest vulnerability to increased insect outbreaks, non-chemical insect control (e.g., baculoviruses), adjusting harvesting schedules, so that those stands most vulnerable to insect defoliation would be harvested preferentially. Under moderate climate changes, these proactive measures may potentially reduce the negative economic consequences of climate change (Shugart *et al.*, 2003). However, as with other primary industry sectors, there is likely to be a gap between the potential adaptations and the realised actions. For example, large areas of forests, especially in developing countries, receive minimal direct human management (FAO, 2000), limiting adaptation opportunities. Even in more intensively managed forests where adaptation activities may be more feasible (Natural Resources Canada, 2002; Shugart *et al.*, 2003) the long time lags between planting and harvesting trees will complicate the decisions as adaptation may take place at multiple times during a forestry rotation.

Marine ecosystems are in some respects less geographically constrained than terrestrial systems. The rates at which planktonic ecosystems have shifted their distribution has been very rapid over the past three decades and this can be regarded as natural adaptation to a changing physical environment (see Chapter 1 and Beaugrand *et al.*, 2002). Most fishing communities are dependent on stocks that fluctuate due to interannual and decadal climate variability and consequently have developed considerable coping capacity (King, 2005). With the exception of aquaculture and some freshwater fisheries, the exploitation by fisheries of natural populations with non-exclusive access to shared resources precludes the kind of management adaptations to climate change suggested for the crop, livestock and forest sectors. Adaptation options thus centre around altering catch size and effort. Three-quarters of world marine fish stocks are currently exploited at levels close to or above their productive capacity (Bruinsma, 2003). Reductions in the level of fishing are therefore required in many cases to sustain yields and may also benefit fish stocks which are sensitive to climate variability when their population age structure and geographic sub-structure is reduced (Brander, 2005). The scope for autonomous adaptation is increasingly restricted as new regulations governing exploitation of fisheries and marine ecosystems come into force. Scenarios of increased level of displacement and migration are likely to put a strain on communal-level fisheries management and resource access systems, and weaken local institutions and services. Despite their adaptive value for the sustainable exploitation of natural resource systems, migrations are seen as a barrier to economic development (Allison *et al.*, 2005).

In contrast to capture fisheries, there are likely to be a range of adaptation options available for aquaculture including the introduction of new species, development of tolerant and resistant varieties of existing species, control of diseases and harmful algal blooms, policy for regulating water demand and forecasting extreme events.

5.5.2 Planned adaptations

Autonomous adaptations may not be fully adequate for coping with climate change, thus necessitating deliberate, planned measures. Many options for planned (i.e., policy-based) adaptation to climate change have been identified for agriculture, forests and fisheries (Aggarwal *et al.*, 2004; Antle *et al.*, 2004; Bryant *et al.*, 2004; Howden, 2003a; Easterling *et al.*, 2004; Kurukulasuriya and Rosenthal, 2003). These can either involve adaptation activities such as developing infrastructure or building the capacity to adapt in the broader user community and institutions often by changing the decision-making environment under which management-level adaptation activities occur (Chapter 17). These factors are likely to have significant influence on adaptation activities even though these generally happen at the enterprise level. There are several pre-conditions for effective adaptation at the management unit level that can be aided by effective planning and capacity building including:

1. To change their management, enterprise managers need to be convinced that the climate changes are real and are likely to continue (e.g. Parson *et al*., 2003; C-CIARN Agriculture, 2002). This will be assisted by policies that maintain climate monitoring and communicate this information effectively. There could be a case also for targeted support of surveillance of pests, diseases, and other factors directly affected by climate.
2. Managers need to be confident by that the projected changes will significantly impact on their enterprise and motivated to change by the knowledge of consequent risks or opportunities (Burton, 2002). This could be assisted by policies that support the research, systems analysis, extension capacity and industry and regional networks that can provide this information.
3. There need to be technical and other options available to respond to the projected changes. The implications of integrating these options into the enterprise should be understood in the context of managers' aspirations, capacity to change and attitude to risk. Where the existing technical options are inadequate to respond to the climate changes, investment in new technical or management options may be required (e.g. improved crop, forage, livestock, forest and fisheries germplasm) or old technologies revived in response to the new conditions (Bass, 2005). This will be assisted by policies that support the development of new germplasm (including via biotechnology: see Box 5.6), techniques and technology and by maintaining the extension capacity to help the flexible recombination of component technologies into production systems.
4. Where there are major land use changes, industry location changes, migration, and the like, then there may be a role for governments to support these transitions via direct financial and material support, creating alternative livelihood options including reduced dependence on agriculture, supporting community partnerships in developing food and forage banks, enhancing capacity to develop social capital and share information, providing food aid and employment to the more vulnerable, developing contingency plans (e.g. Olesen and Bindi, 2002; Winkels and Adger, 2002; Holling, 2004). Effective planning for and management of such transitions may also result in less habitat loss, less risk of carbon loss (e.g. Goklany, 1998) and also lower environmental costs such as soil degradation, siltation and reduced biodiversity (Stoate *et al.*, 2001).
5. Develop new infrastructure, policies and institutions to support the new management and land use arrangements including through addressing climate change in development programs, enhanced investment in irrigation infrastructure and efficient water use technologies, ensuring appropriate transport and storage infrastructure, revising land tenure arrangements including attention to well-defined property rights (FAO, 2003), establishment of accessible, efficiently-functioning markets for products and inputs (seed, fertiliser, labour etc) and for financial services including insurance (Turvey, 2001), support for ongoing reduction of market

and trade barriers (e.g. WTO rounds).

6. The capacity to make continuing adjustments and improvements in adaptation by understanding what is working, what is not and why via targeted monitoring of adaptations to climate change and their costs and effects (Perez and Yohe, 2005).

It is important to note that the above planned adaptations to climate change will interact with, depend on or perhaps even be just a subset of policies on natural resource management, human and animal health, governance and political rights amongst many others: the 'mainstreaming' of climate change adaptation into policies intended to enhance broad resilience (Chapter 17.4.2). The capacity to plan and implement adaptation at local, national and international levels, in most sectors of economy including agriculture and forestry, remains largely untested and uncertain. Moreover, it is difficult to assess in an *ex ante* sense the capacity to adapt, because there is a limited understanding of the processes that govern political decision making and institutional change in response to global changes (Dietz *et al.*,). Nevertheless, the patterns of technological innovation in agriculture (often involving public research institutions) have generally served to reduce the dependence on the scarce resources (Hayami and Ruttan, 1985). Stable political and economic systems that address underlying causes of social vulnerability are also likely to be critical in allowing primary industry managers and communities to effectively adapt (Eakin, 2000; Kelly, 2000).

Box 5.5: Will Biotechnology Assist Agricultural and Forest Adaptation?

Breakthroughs in molecular genetic mapping of the plant genome have led to the identification of bio-markers that are closely linked to known resistance genes such that their isolation is clearly feasible in the future. Two forms of stress resistance especially relevant to climate change are drought and temperature. A number of studies have demonstrated genetic modifications to target plants that increased their water-deficit tolerance (as reviewed by Cheikh *et al.*, 2000; Pilon-Smits *et al.*, 1995; Drennen *et al.*, 1993; Kishor *et al.*, 1995). Concern that water stress resistance found in the narrow range of target plants may not extend to the wider range of crop plants exists among researchers but they agree that the potential for progress is high. Cheikh *et al.* (2000) point out that less effort has gone into genetic engineering for high-temperature resistance than low temperature resistance. It is generally believed that plant cells respond to heat stress through the expression of heat shock proteins and that heat-tolerance gain may be possible by engineering plants to over-express such proteins (Hinderhofer *et al.*, 1998). Yet, many research challenges lie ahead. Little is known about how the desired traits achieved by genetic modification perform in real farming and forestry applications. Moreover, alteration of a single physiological process often is compensated or dampened so that little change in plant growth and yield is achieved from modification of a single physiological process (Sinclair and Purcell, 2005). Although biotechnology is not expected to replace conventional agronomic breeding, Cheikh *et al.*, 2000 and FAO, 2004a argue that it will be a crucial adjunct to conventional breeding – both likely will be needed to meet future environmental challenges, including climate change.

5.6 Costs and other socioeconomic aspects, including food supply and security

5.6.1 Global costs to agriculture

Fischer *et al.*, 2002 quantify the impact of climate change on global agricultural GDP by 2080 as between -1.5% and + 2.6% with considerable regional variation. Overall, temperate zone agriculture stands to benefit while agriculture in the tropics will be adversely affected. Fischer *et al.* (2002) however suggest that, taking into account economic adjustment, global cereal production by 2080 falls within a 2% boundary of the no-climate change reference production.

Impacts of climate change on world food prices are summarized in Figure 5.4. Overall, the effects of higher GMT on food prices follow the expected changes in crop and livestock production. Higher output associated with a moderate increase in the GMT is likely to result in a small decline in real world prices for food (cereals), while GMT changes towards 5.5°C and above could lead to a pronounced increase in food prices of, on average, 30%.

5.6.2 Global costs to forestry

Alig *et al.* (2004) suggest that climate variability and climate change may alter the productivity of forests thereby shifting resource management, economic processes of adaptation and forest harvests both nationally and regionally. Such changes may also alter the supply of products to national and international markets as well as change the prices of forest products and economic welfare. Current studies consider mainly impact of climate change on forest resources, industry and economy however some analyses include feedbacks in the ecological system and with the greenhouse gas cycling in forest ecosystems and forest products (e.g., Sohngen *et al.*,). There are a number of studies analyzing the effects of climate change on the forest industry and the economy (e.g. Binkley, 1988; Joyce, 1995; Perez-Garcia, 1997; Sohngen, 1998, Shugart *et al.*, 2003).

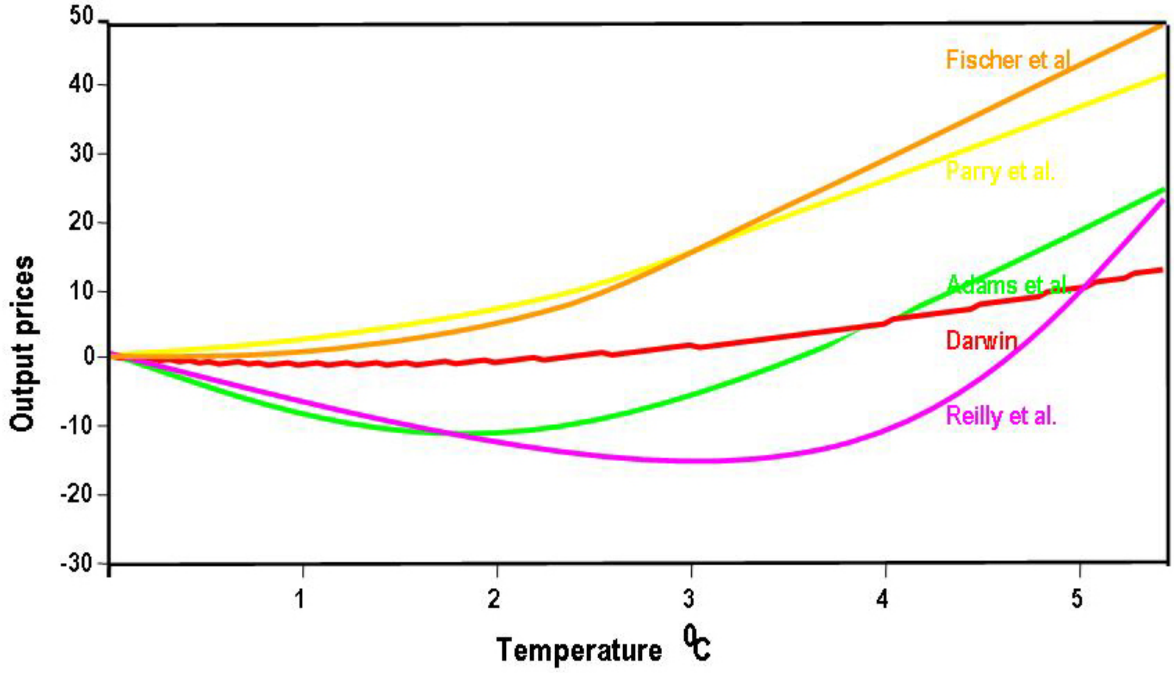


Figure 5.4: *Food prices (percent of baseline) versus global mean temperature change for major modelling studies. Prices interpolated from point estimates of temperature effects.*

If the world develops as the models predict, there will be a general decline of the wood raw material prices due to increased wood production (Perez-Garcia, 1997; Sohngen, 1998). The same authors conclude that the economic welfare effects are relatively small but positive with net benefits accruing to wood consumers. With respect to the non-wood services from the forest resources there is no solid global analysis carried out but the impacts of climate change on many these services will likely be spatially specific.

5.6.3 Changes in trade

The principal impact of climate change on agriculture is an increased production potential in temperate-zones and a declining one in the tropics. This relocation of production potentials is expected to result into higher trade flows of temperate zones products (e.g. cereals and livestock products) to the tropics. Fischer *et al.*, 2002 estimate that cereal imports by developing countries would rise by 10-40% by 2080. A freer trading environment in agriculture would help facilitate these changes in regional supply and demand.

5.6.4 Regional costs and associated socioeconomic impacts

Fischer *et al.* (2002) quantify the impacts for major countries and country groups as follows: globally there will be major gains in potential agricultural land by 2080, particularly in North America (20-50%) and the Russian Federation (40-70%). Losses of up to 9% are predicted for sub-Saharan Africa. The regions that are likely to face the biggest challenges to their food security situation will be Africa, particularly sub-Saharan Africa as well as Asia, particularly South Asia (FAO, 2006).

Africa

Yields of grains and other crops could decrease substantially across the African countries due to increased frequency of drought, even if potential production should rise because of the increase in CO_2 concentrations. Some crops (e.g. maize) could be lost in some areas. Livestock production would suffer due to deterioration in the quality of rangeland associated with higher concentrations of atmospheric carbon dioxide and to changes in areas of rangeland (increase of unproductive shrub-land and desert). Socio-economic factors influence responses to changes in crop productivity, with price changes and shifts in comparative advantage (Parry *et al.*, 2004).

Asia

According to Murdiyarso (2000) rice production in Asia could decline by 3.8% over the current century. Similarly, a 2 ^{o}C increase in mean air temperature could decrease rice yield by about 0.75 tonne/ha in India and rain-fed rice in China could decrease by 5-12% (Lin *et al.*, 2004). Suitability for wheat growing could decrease in large portions of South Asia and the southern part of East Asia (Fischer *et al.*, 2002). For example, a 0.5 ^{o}C increase in winter temperature would reduce wheat yield by 0.45 ton/ha in India (Naveen *et al.*, 2003) and Chinese rain-fed wheat production could decrease by 4 to7% by 2050, but wheat production would increase from 6.6 to 25.1% in 2050 if the CO_2 fertilization effect is taken into account (Lin *et al.*, 2004).

5.6.5 Food security and vulnerability

For assessing the potential food security implication of climate change, four dimensions are important: the effects on food availability, on access to food, on stability, and on utilisation (FAO, 2003a).

Food Availability

Food availability depends on the actual production of food, but also on trade flows, stocks, and food aid. Climate change will result in mixed and geographically varying impacts on food availability (FAO, 2005b and FAO, 2003b). Globally an increased agricultural production potential due to climate change should improve food availability (Fischer *et al.*, 2002), but this overall improvement is likely to mask considerable differences at the regional and local level. A reduction in the production potential of tropical developing countries, many of which are already faced with serious food insecurity, would add to the burden of such countries (Fischer *et al.*, 2002).

Stability

Alterations in the patterns of extreme events, such as increased frequency and intensity of droughts, according to FAO (FAO, 2005b) will have much more serious consequences for chronic and transitory food insecurity than will shifts in the patterns of average temperature and precipitation. Frequent localized increases in food prices could be expected in areas with high transportation costs and other barriers to trade. Subsistence producers growing orphan crops, such as sorghum, millets, etc, are likely to be at the greatest risk. Humid areas are also vulnerable to climate variability. They can suffer from changes in the length of the growing season and from extreme events, such as tropical cyclones. Food insecurity and loss of livelihood would be further exacerbated by the loss of cultivated land and nursery areas for fisheries through inundation and coastal erosion in low-lying areas of the tropics (FAO, 2005a).

Utilisation

There are a number of potential effects of climate change on nutrition and food utilisation. These need to be seen in close connection with other health-related aspects (see Chapter 8). Some studies (e.g. IPCC, 2001) suggest decreased water availability for populations in already water-scarce regions, particularly in the sub-tropics. In other areas the risk of flooding of human settlements increase, from both sea level rise and increased heavy precipitation may result in an increase in the number of people exposed to vector-borne (e. g. malaria), and water-borne diseases (e.g. cholera). The links between climate change and health issues affect not only the nutritional uptake of food, but also through its direct effects, the availability of labour.

Overall, climate change could increase the number of people at risk of hunger (FAO, 2005a). In some 40 poor, developing countries, with a combined population of 2 billion, including 450 million undernourished people, production losses due to climate change may drastically increase the number of undernourished people, severely hindering progress in combating poverty and food insecurity (FAO, 2005b).

5.7 Implications for sustainable development

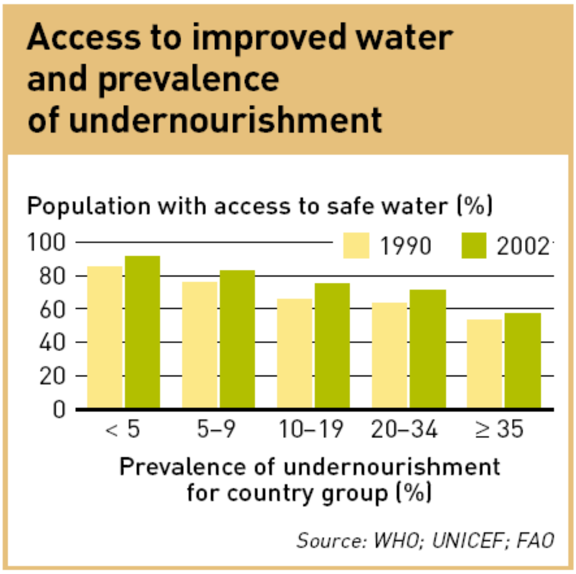
Sustainable economic development and poverty reduction remain top priorities for developing countries (Aggarwal *et al.*, 2004). Any climate change adaptation measures should be closely integrated into, overall development strategies and programmes, into country programmes, Poverty Reduction Strategy Programmes (Eriksen and Naess, 2003 and Pro- Poor strategies; Kurukulasuriya and Rosenthal, 2003), and be understood as a “shared responsibility” (Ravindranath and Sathaye, 2002 in: Climate change and developing countries: 86).

There are a number of international initiatives that could help make adaptation measures to climate change conducive to sustainable development, both in terms of socio-economic and environmental sustainability. A broad and important initiative toward more sustainable overall development is the pledge of world leaders to achieve by 2015 a set of eight development objectives: the Millennium Development Goals (MDGs)

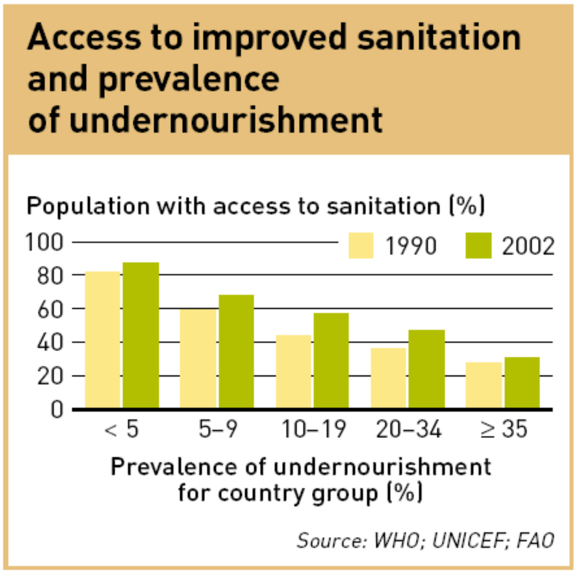
The MDGs established several targets for ensuring environmental sustainability. Key indicators include measures of deforestation and use of solid fuels, as well as access to improved water and sanitation facilities. Climate change poses an extra challenge in achieving these goals but appropriate adaptation to it also affords an extra opportunity to meeting them. The following examples illustrate the main challenges (FAO, 2005c).

Worldwide, forests were felled and burned during the 1990s at a rate of 9.4 million hectares a year (an area roughly the size of Portugal). In proportional terms, the most rapid deforestation took place in

Africa and the Caribbean and among the countries with the least sustainable forms of agriculture and highest prevalence of hunger. These countries are marked by the highest reliance on solid fuels, the lowest levels of access to safe water and sanitation and the slowest progress towards the MDG targets (see Figures 5.5a, 5.5b and 5.5c).

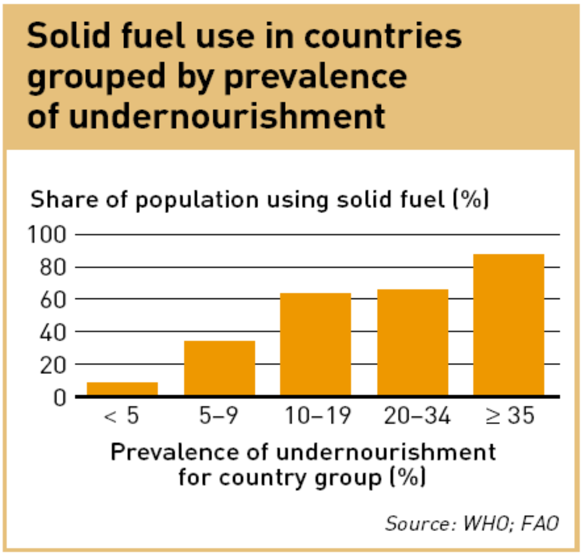


(a)



(b)

Figure 5.5a,b,c: Progress toward selected Millennium Development Goal targets



(c)

An estimated 350 million people depend on forests as their primary source of income and food. Wild plants, animals and other forest foods are important to the diets and food security of an estimated 1 billion people. Forests also provide grazing and fodder for many of the 500 million poor livestock producers whose livelihoods depend on keeping a few animals. Particularly in countries where hunger is widespread, most of the rural poor burn wood gathered from forests and other solid fuels to cook their food (see Figure 5.5c).

A large proportion of the hungry is concentrated in areas that are vulnerable to environmental degradation and climate change, including forests and semi-arid rangelands. When food is scarce, hunger can drive them to plough under or overgraze fragile rangelands and forest margins, threatening the very resources upon which they depend.

5.8 Key Conclusions and their Uncertainties, Confidence Levels, Research Gaps

5.8.1 Findings and Key Conclusions

While moderate warming benefits crop and pasture yields in temperate regions, even slight warming decreases yields in seasonally dry and tropical regions (*medium confidence*). The preponderance of evidence from models suggests that moderate local increases in temperature (to 3ºC) can have small beneficial impacts on major rainfed crops (maize, wheat, rice) and pastures in temperate regions but even slight warming in seasonally dry and tropical regions reduces yield. Further warming has increasingly negative impacts in all regions. [5.4.2][See Figure 5.2]. Furthermore, modelling studies that include extremes in addition to changes in mean climate show lower crop yields than for changes in means alone, strengthening similar TAR conclusions. [5.4.1] A change in frequency of extreme events is likely to disproportionately impact small-holder farmers and artisan fishers. [5.4.7]

New experimental research on CO_2 fertilisation suggests smaller effects on crop and forest systems than earlier experimental results suggested – however, crop models include CO_2 estimates close to the upper range of new research (*high confidence*) while forest models may overestimate CO_2 effects *(medium confidence)*. Recent results from meta-analyses of Free Air Carbon Enrichment (FACE) studies of carbon dioxide fertilisation confirm conclusions from the TAR that crop yields at 550 ppm CO2 concentration increase by an average of 15%. Crop model estimates of CO2 fertilisation are in the range of FACE results. [5.4.1.1]. Results from the FACE studies of CO2 enrichment to 550 ppm on trees suggest a smaller overall effect than is assumed by some of the forest sector models [5.4.1.1].

Globally, forestry production is estimated to change only modestly with climate change in the short and medium term (high confidence). Local extinctions of particular fish species are expected at edges of ranges (*high confidence*). Overall, global forest products output at 2020 and 2050 changes, ranging from a modest increase to a slight decrease depending on the assumed impact of CO2 fertilisation and the effect of processes not well represented in the models (e.g., pest effects), although regional and local changes will be large. [5.4.5.2] Regional changes in the distribution and productivity of particular fish species will continue and local extinctions will occur at the edges of ranges, particularly in freshwater and diadromous species (e.g. salmon, sturgeon). In some cases ranges and productivity will increase. [5.4.6] Emerging evidence suggests concern that meridional overturning circulation is slowing down, with serious potential consequences for fisheries. [5.4.6]

Food and forestry trade is projected to increase in response to climate change, with increased food import-dependence of most developing countries (*medium to low confidence*). While the purchasing power for food is reinforced in the period to 2050 by declining real prices, it would be adversely affected by higher real prices for food from 2050 to 2080. [5.6.1, 5.6.2] Food security in many of the regions expected to suffer more severe yield declines is already challenged. Agricultural and forestry trade flows are foreseen to rise significantly. Exports of temperate zone food products to tropical countries will rise, [5.6.2] while the reverse may take place in forestry. [5.4.5]

Simulations suggest rising relative benefits of adaptation with low to moderate warming (*medium confidence)*, although adaptation may stress water and environmental resources as warming increases (*low confidence*). There are multiple adaptation options that imply different costs, ranging from changing practices in place to changing locations of FFFF activities [5.5.1]. The potential effectiveness of the adaptations varies from only marginally reducing negative impacts to in some cases changing a negative impact into a positive impact. On average in cereal cropping systems adaptations such as changing varieties and planting times enable avoidance of a 10-15% reduction in yield. The benefit from adapting tends to increase with the degree of climate change up to a point

[Figure 5.2]. Pressure to cultivate marginal land or to adopt unsustainable cultivation practices as yields drop may increase land degradation and endanger biodiversity of both wild and domestic species. Climate changes increase irrigation demand in the majority of world regions due to a combination of decreased rainfall and increased evaporation arising from increased temperatures, which combined with expected reduced water availability, adds another challenge to future water and food security. [5.7]

Summary of Impacts and Adaptive Results by Temperature and Time. Major generalizations across the FFFF sectors distilled from the literature are reported either by increments of temperature increase (Table 5.5) or by increments of time (Table 5.6), depending on how the information is originally reported. A global map of regional impacts of FFFF is shown in Figure 5.6.

Table 5.5: *Summary of Selected Conclusions for Food, Fibre, Forestry, and Fisheries, by Warming Increments.*

Temp. Change	Sub-sector	Region	Finding	Source Section
+1-2°C	Forestry	Global	--Timber production +5%	Table 5.3
	Food crops	Temperate	--Cold limitation alleviated for all crops. --Adaptation of maize and wheat increases yield 10-15%; rice yield no change—regional variation is high	Fig. 5.2
	Pastures and Livestock		-- Cold limitation alleviated for pastures; seasonal increased frequency of heat stress for livestock	Table 5.2
	Food crops	Tropical	--Wheat and maize yields reduced below baseline levels. Rice is unchanged. --Adaptation of maize, wheat, rice maintains yield at current levels;	Fig. 5.2
	Pastures and Livestock	Semi-arid	-- No increase in net primary productivity; seasonal increased frequency of heat stress for livestock	Table 5.2
	Prices	Global	-- Agricultural prices: -10- -30%	Fig. 5.4
+2-3°C	Forestry	Global	--Timber production +20%	Table 5.3
	Food crops		--550 ppm CO_2 (approx. equal to +2°C) increases C3 crop yield by 17%; this increase is offset by temperature increase of 2˚C assuming no adaptation and 3˚C with adaptation.	Fig. 5.2
	Prices		-- Agricultural prices: -10- +20%	Fig 5.4
	Food crops	Temperate	--Adaptation increases all crops above baseline yield	Fig 5.2
	Fisheries		--Positive effect on trout in winter, negative in summer	5.4.6.1
	Pastures and livestock		-- Moderate production loss in swine and confined cattle	Table 5.2
	Pastures and livestock	Semi-arid	-- Reduction in animal weight, pasture production, and increased heat stress for livestock	Table 5.2
	Food crops	Tropical	--Adaptation maintains yields of all crops above baseline; yields drops below baseline for all crops without adaptation.	Fig 5.2

+3-5°C	Forestry Prices and Trade	Global	--Timber production +30%, regional variation 4-66% --Reversal of downward trend in wood prices -- Agricultural prices: +10- +40% -- Cereal imports of developing countries to increase by 10-40%.	Table 5.3 5.4.5.1 Fig. 5.4 5.6.3
	Forestry Food crops	Temperate	--Increase in fire hazard and insect damage --Adaptation maintains yields of all crops above baseline; yield drops below baseline for all crops without adaptation.	5.4.5.3 Fig 5.2
	Pastures and Livestock		--Strong production loss in swine and confined cattle	Table 5.2
		Tropical	--Maize and wheat yields reduced below baseline regardless of adaptation, but adaptation maintains rice yield at baseline levels.	Fig 5.2
	Pastures and Livestock	Semi-arid	--Reduction in animal weight and pasture growth. Increased animal heat stress and mortality.	Table 5.2

Table 5.6: *Summary of Selected Findings for Food, Fibre, Forestry, and Fisheries, by Time Increment.*

Time slice	**Sub-sector**	**Location**	**Finding**	**Source**
2020	Food crops	USA	--Extreme events, i.e., increased heavy precipitation, cause crop losses to $3 B by 2030 with respect to current levels	5.4.2
	Small-holder farming, fishing	Tropical, esp. E. and S. Africa	--Decline in maize yields, increased risk of crop failure, high livestock mortality	5.4.7
	Small-holder farming, fishing	Tropical, esp. S. Asia	--Early snow melt causing spring flooding and summer irrigation shortage	5.4.7
	Forestry	Global	--Increase export of timber from temperate to tropical countries --Increase in share of timber production from plantations	5.4.5.2
2050	Fisheries	Global	--Marine primary production +0.7-8.1%, with large regional variation (see Ch 4)	5.4.6.2
	Food crops	Global	--With adaptation, yields of wheat, rice, maize above baseline levels in the Temperate Zones and at baseline levels in the Tropics.	Fig 5-2
2080	Food crops	Global	--Crop irrigation water requirement increases 5-20%, with range due to significant regional variation	5.4.2
	Agriculture sector	Global	--Stabilization at 550 ppm ameliorates 70-100% of agricultural cost caused by unabated climate change	5.4.2

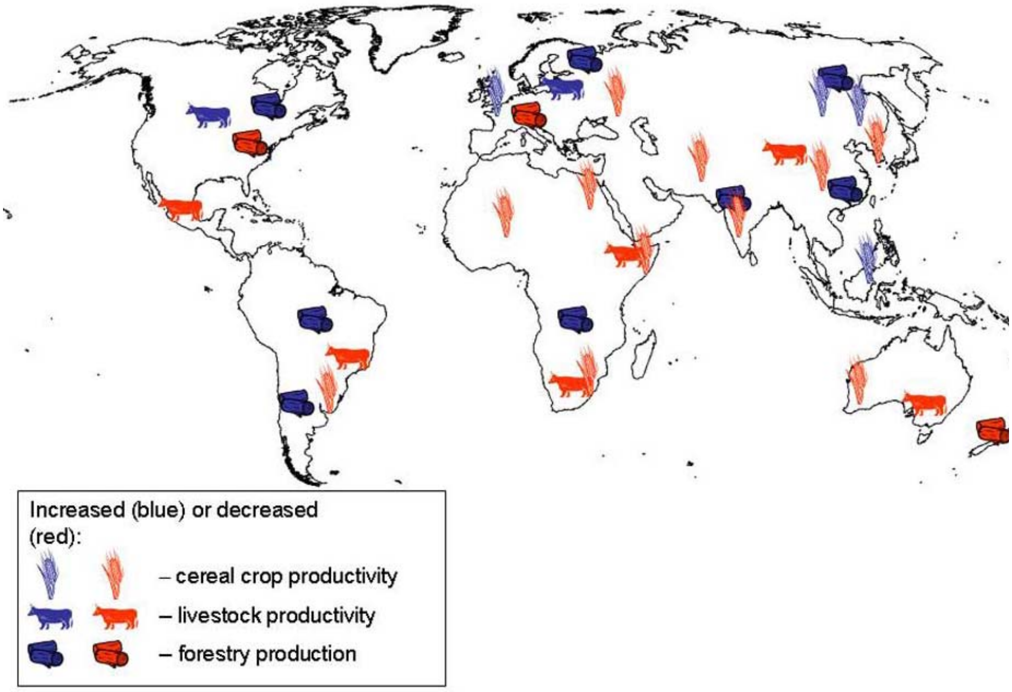


Figure 5.6: *Major impacts of climate change on crop and livestock yields, and forestry production by 2050 based on literature and expert judgment of Chapter 5 Lead Authors. Adaptation is not taken into account.*

5.8.2 Research Gaps and Priorities

Key knowledge gaps hindering assessments of climate change consequences for FFFF and their accompanying research priorities are listed in Table 5.7.

Table 5.7: *Key Knowledge Gaps and Research Priorities for Food, Fibre, Forestry, and Fisheries*

Knowledge Gap	Research Priority
There is a lack of knowledge of CO_2 response for many crops other than cereals, including many of importance to the rural poor, such as root crops, millet.	FACE type experiments needed on expanded range of crops, pastures, forests, and locations, especially in developing countries.
Understanding of the combined effects of elevated CO_2 and climate change on pests, weeds and disease is insufficient.	Basic knowledge of pest, disease, weed response to elevated CO_2 and climate change needed.
Much uncertainty of how changes in frequency and severity of extreme climate events with climate change will affect all sectors remains.	Improved prediction of future impacts of climate change requires better representation of climate variability at scales from short term (including extreme events), to interannual and decadal in FFFF models.
Calls by the TAR to enhance crop model inter-comparison studies have remained largely unheeded.	Improvements and further evaluation of economic/trade/technological components within integrated assessment models are needed.
Few experimental or field studies have investigated the impacts of future climate scenarios on aquatic biota.	Future trends in aquatic primary production depend on nutrient supply and on temperature sensitivity of primary production. Both of these could be improved with a relatively small research effort.

In spite of a decade of prioritization, adaptation research has failed to provide generalized knowledge of adaptive capacity of FFFF systems across a range of climate and socioeconomic futures, and across developed and developing countries (including commercial and small-holder operations).	A fuller range of adaptation strategies must be examined in modelling frameworks in FFFF. Accompanying research that estimates the costs of adaptation is needed. Assessments of how to move from potential adaptation options to adoption taking into account decision-making complexity, diversity at different scales and regions, non-linearities and timelags in responses and biophysical, economic, institutional and cultural barriers to change are needed. Particular emphasis to developing countries should be given.
The global impacts of climate change on agriculture and food security will depend on the future role of agriculture in the global economy. While most studies available for the FAR assumed a rapidly declining role of agriculture in the overall generation of income, no consistent and comprehensive assessment was available.	Given the importance of this assumption, more research is needed to assess the future role of agriculture in overall income formation (and dependence of people on agriculture for income generation and food consumption) in essentially all developing countries; such an exercise could also afford an opportunity to review the assumption made in the various SRES scenarios and address the critique re the overall economic plausibility of these scenarios.
Relatively moderate impacts of climate change on the overall agro-ecological conditions are likely to mask much more severe climatic and economic vulnerability at the local level. Little is known about such vulnerability.	More research is required to identify highly vulnerable micro-environments and associated households and to provide agronomic and economic coping strategies for the affected populations.

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