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Food, fibre and forest products

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Executive summary

In mid- to high-latitude regions, moderate warming benefits crop and pasture yields, but even slight warming decreases yields in seasonally dry and low-latitude regions (medium confidence).

Modelling results for a range of sites find that, in mid- to high-latitude regions, moderate to medium local increases in temperature (1-3ºC), along with associated carbon dioxide (CO_2) increase and rainfall changes, can have small beneficial impacts on crop yields. In low-latitude regions, even moderate temperature increases (1-2°C) are likely to have negative yield impacts for major cereals. Further warming has increasingly negative impacts in all regions (medium to low confidence) [Figure 5.2]. These results, on the whole, project the potential for global food production to increase with increases in local average temperature over a range of 1 to 3ºC, but above this range to decrease [5.4, 5.6].

The marginal increase in the number of people at risk of hunger due to climate change must be viewed within the overall large reductions due to socio-economic development (medium confidence).

Compared to 820 million undernourished today, the IPCC Special Report on Emissions Scenarios (SRES) scenarios of socio-economic development without climate change project a reduction to 100-230 million (range is over A1, B1, B2 SRES scenarios) undernourished by 2080 (or 770 million under the A2 SRES scenario) (medium confidence). Scenarios with climate change project 100-380 million (range includes with and without CO_2 effects and A1, B1, B2 SRES scenarios) undernourished by 2080 (740-1,300 million under A2) (low to medium confidence). Climate and socio-economic changes combine to alter the regional distribution of hunger, with large negative effects on sub-Saharan Africa (low to medium confidence) [Table 5.6].

Projected changes in the frequency and severity of extreme climate events have significant consequences for food and forestry production, and food insecurity, in addition to impacts of projected mean climate (high confidence).

Recent studies indicate that climate change scenarios that include increased frequency of heat stress, droughts and flooding events reduce crop yields and livestock productivity beyond the impacts due to changes in mean variables alone, creating the possibility for surprises [5.4.1, 5.4.2]. Climate variability and change also modify the risks of fires, and pest and pathogen outbreaks, with negative consequences for food, fibre and forestry (FFF) (high confidence) [5.4.1 to 5.4.5].

Simulations suggest rising relative benefits of adaptation with low to moderate warming (medium confidence), although adaptation stresses 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 FFF activities [5.5.1]. Adaptation effectiveness varies from only marginally reducing negative impacts to changing a negative impact into a positive one. On average, in cereal cropping systems worldwide, adaptations such as changing varieties and planting times enable avoidance of a 10-15% reduction in yield corresponding to 1-2°C local temperature increase. The benefit from adapting tends to increase with the degree of climate change up to a point [Figure 5.2]. Adaptive capacity in low latitudes is exceeded at 3°C local temperature increase [Figure 5.2, Section 5.5.1]. Changes in policies and institutions will be needed to facilitate adaptation to climate change. Pressure to cultivate marginal land or to adopt unsustainable cultivation practices as yields drop may increase land degradation and resource use, and endanger biodiversity of both wild and domestic species [5.4.7]. Adaptation measures must be integrated with development strategies and programmes, country programmes and Poverty Reduction Strategies [5.7].

Smallholder and subsistence farmers, pastoralists and artisanal fisherfolk will suffer complex, localised impacts of climate change (high confidence).

These groups, whose adaptive capacity is constrained, will experience the negative effects on yields of low-latitude crops, combined with a high vulnerability to extreme events. In the longer term, there will be additional negative impacts of other climate-related processes such as snow-pack decrease (especially in the Indo-Gangetic Plain), sea level rise, and spread in prevalence of human diseases affecting agricultural labour supply. [5.4.7]

Globally, commercial forestry productivity rises modestly with climate change in the short and medium term, with large regional variability around the global trend (medium confidence).

The change in the output of global forest products ranges from a modest increase to a slight decrease, although regional and local changes will be large [5.4.5.2]. Production increase will shift from low-latitude regions in the short-term, to high-latitude regions in the long-term [5.4.5].

Local extinctions of particular fish species are expected at edges of ranges (high confidence).

Regional changes in the distribution and productivity of particular fish species are expected due to continued warming 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 that meridional overturning circulation is slowing, with serious potential consequences for fisheries (medium confidence) [5.4.6].

Food and forestry trade is projected to increase in response to climate change, with increased dependence on food imports for 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].

Exports of temperate zone food products to tropical countries will rise [5.6.2], while the reverse may take place in forestry in the short-term. [5.4.5]

Experimental research on crop response to elevated CO_2 confirms Third Assessment Report (TAR) findings (medium to high confidence). New Free-Air Carbon Dioxide Enrichment (FACE) results suggest lower responses for forests (medium confidence).

Recent re-analyses of FACE studies indicate that, at 550 ppm atmospheric CO_2 concentrations, yields increase under unstressed conditions by 10-25% for C_3 crops, and by 0-10% for C_4 crops (medium confidence), consistent with previous TAR estimates (medium confidence). Crop model simulations under elevated CO_2 are consistent with these ranges (high confidence) [5.4.1]. Recent FACE results suggest no significant response for mature forest stands, and confirm enhanced growth for young tree stands [5.4.1.1]. Ozone exposure limits CO_2 response in both crops and forests.

5.1 Introduction: importance, scope and uncertainty, Third Assessment Report summary, and methods

5.1.1 Importance of agriculture, forestry and fisheries

At present, 40% of the Earth's land surface is managed for cropland and pasture (Foley et al., 2005). Natural forests cover another 30% (3.9 billion ha) of the land surface with just 5% of the natural forest area (FAO, 2000) providing 35% of global roundwood. 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 United Nations Food and Agriculture Organization (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% of their average per capita animal protein intake, but three-quarters of global fisheries are currently fully exploited, overexploited or depleted (FAO, 2004c).

5.1.2 Scope of the chapter and treatment of uncertainty

The scope of this chapter, with a focus on food crops, pastures and livestock, industrial crops and biofuels, forestry (commercial forests), aquaculture and fisheries, and small-holder and subsistence agriculturalists and artisanal fishers, is to:

- examine current climate sensitivities/vulnerabilities;
- consider future trends in climate, global and regional food security, forestry and fisheries production;
- 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;
- assess the effectiveness of adaptation in offsetting damages and identify adaptation options, including planned adaptation to climate change;
- examine the social and economic costs of climate change in those sectors; and,
- 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 judgements 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 summarise those findings and conclusions and provide a final judgement of their uncertainties.

5.1.3 Important findings of the Third Assessment Report

The key findings of the 2001 Third Assessment Report (TAR; IPCC, 2001) 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 temperature, but decrease once optimal temperatures are exceeded for a range of processes, especially plant water use. The CO_2 effect may be relatively greater (compared to that for irrigated crops) for crops under moisture stress.
- Modelling studies suggest crop yield losses with minimal warming in the tropics.
- Mid- to high-latitude crops benefit from a small amount of warming (about +2°C) but plant health declines with additional warming.
- 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 findings of the Second Assessment Report (SAR), climate change will increase global timber supply and enhance existing market trends of rising market share in developing countries.

Aquaculture and fisheries

- Global warming will confound the impact of natural variation on fishing activity and complicate management.
- 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 on agriculture, forestry and fisheries is addressing deepening levels of system complexity that require a new suite of methodologies to cope with the added uncertainty that accompanies the addition of new, often non-linear, process knowledge. The added realism of experiments (e.g., FACE) and the translation of experimental results to process crop-simulation models are adding confidence to model estimates. Integrated physiological and economic models (e.g., Fischer et al., 2005a) allow holistic simulation of climate change effects on agricultural productivity, input and output prices, and risk of hunger in specific regions, although these simulations rely on a small set of component models. The application of meta-analysis to agriculture, forestry and fisheries in order to identify trends and consistent findings across large numbers of studies has revealed important new information since the TAR, especially on the direct effects of atmospheric CO_2 on crop and forest productivity (e.g., Ainsworth and Long, 2005) and fisheries (Allison et al., 2005). The complexity of processes that determine adaptive capacity dictates 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 increases the need for more robust methods to scale local findings to larger regions, such as the use of multi-level modelling (Easterling and Polsky, 2004). Further complexity is contributed by the growing number of scenarios of future climate and society that drive inputs to the models (Nakićenović 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 of photoperiod (e.g., Leff et al., 2004). 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.

Crops exhibit threshold responses to their climatic environment, which affect their growth, development and yield (Porter and Semenov, 2005). Yield-damaging climate thresholds that span periods of just a few days for cereals and fruit trees include absolute temperature levels linked to particular developmental stages that condition the formation of reproductive organs, such as seeds and fruits (Wheeler et al., 2000; Wollenweber et al., 2003). This means that yield damage estimates from coupled crop–climate models need to have a temporal resolution of no more than a few days and to include detailed phenology (Porter and Semenov, 2005). Short-term natural extremes, such as storms and floods, interannual 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, El Niño-like conditions increase the probability of farm incomes falling below their long-term median by 75% across most of Australia's cropping regions, with impacts on gross domestic product (GDP) ranging from 0.75 to 1.6% (O'Meagher, 2005). Recently the winter North Atlantic Oscillation (NAO) has been shown to correlate with the following summer's climate, leading to sunnier and drier weather during wheat grain growth and ripening in the UK and, hence, to better wheat grain quality (Atkinson et al., 2005); but these same conditions reduced summer growth of grasslands through increased drought effects (Kettlewell et al., 2006).

The recent heatwave in Europe (see Box 5.1) and drought in Africa (see Table 5.1) illustrate the potentially large effects of local and/or regional climate variability on crops and livestock.

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 (see Box 5.2), are increasing sensitivity to climate change and reducing resilience in the agricultural sector

Box 5.1. European heatwave 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 (see Trenberth et al., 2007). A record drop in crop yield of 36% occurred in Italy for maize grown in the Po valley, where extremely high temperatures prevailed (Ciais et al., 2005). In France, compared to 2002, the maize 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 (e.g., maize, 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 COGECA, 2003b). Wine production in Europe was the lowest in 10 years (COPA COGECA, 2003a). The (uninsured) economic losses for the agriculture sector in the European Union were estimated at €13 billion, with largest losses in France (€4 billion) (Sénat, 2004).

Table 5.1. *Quantified impacts of selected African droughts on livestock, 1981 to 1999.*

Date	Location	Mortality and species	Source
1981-84	Botswana	20% of national herd	FAO, 1984, cited in Toulmin, 1986
1982-84	Niger	62% of national cattle herd	Toulmin, 1986
1983-84	Ethiopia (Borana Plateau)	45-90% of calves, 45% of cows, 22% of mature males	Coppock, 1994
1991	Northern Kenya	28% of cattle 18% of sheep and goats	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 nine pastoral areas)	20% of cattle 20% of sheep and goats	Ndikumana et al., 2000
1995-97	Southern Ethiopia	46% of cattle 41% of sheep and goats	Ndikumana et al., 2000
1998-99	Ethiopia (Borana)	62% of cattle	Shibru, 2001, cited in Desta and Coppock, 2002

Box 5.2. Air pollutants and ultraviolet-B radiation (UV-B)

Ozone has significant adverse effects on crop yields, pasture and forest growth, and species composition (Loya et al., 2003; Ashmore, 2005; Vandermeiren, 2005; Volk et al., 2006). While emissions of ozone precursors, chiefly nitrous oxide (NO_x) 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 et al., 2005; Fiscus et al., 2005). Although several studies confirm TAR findings that elevated CO_2 may ameliorate otherwise negative impacts from ozone (Kaakinen et al., 2004), the essence of the matter should be viewed the other way around: increasing ozone concentrations in future decades, with or without CO_2 increases, with or without climate change, will negatively impact plant production, possibly increasing exposure to pest damage (Ollinger et al., 2002; Karnosky, 2003). Current risk-assessment tools do not sufficiently consider these key interactions. Improved modelling approaches that link the effects of ozone, climate change, and nutrient and water availability on individual plants, species interactions and ecosystem function are needed (Ashmore, 2005): some efforts are under way (Felzer et al., 2004). Finally, impacts of UV-B exposure on plants were previously reviewed by the TAR, which showed contrasting results on the interactions of UV-B exposure with elevated CO_2. Recent studies do not narrow the uncertainty: some findings suggest amelioration of negative UV-B effects by elevated CO_2 (Qaderi and Reid, 2005); others show no effect (Zhao et al., 2003).

(FAO, 2003a). Natural land resources are being degraded through soil erosion, salinisation of irrigated areas, dryland 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, and loss of biodiversity and erosion of the genetic resource base when modern varieties displace traditional ones (FAO, 2003b). Small-holder agriculturalists are especially vulnerable to a range of social and environmental stressors (see Table 5.2). The total effect of these processes on agricultural productivity is not clear. Additionally, multiple stresses, such as forest fires and insect outbreaks, increase overall sensitivity (see Section 5.4.5). In fisheries, overexploitation of stocks (see Section 5.4.6), loss of biodiversity, water pollution and changes in water resources (see Box 5.3) also increase the current sensitivity to climate.

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., 2005). 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 changing conditions. A comparison of conditions on both sides of the USA–Mexico border reveals how social, political, economic and historical factors contribute to differential vulnerability among farmers and ranchers living within the same biophysical regime (Vasquez-Leon et al., 2003). Institutional and economic reforms linked to globalisation processes (e.g., removal of subsidies, increased import competition) reduce the capacity of some farmers to respond to climate variability (O'Brien et al., 2004). Efforts to reduce vulnerability and facilitate adaptation to climate change are influenced both positively and negatively by changes associated with globalisation (Eakin and Lemos, 2006).

Table 5.2. *Multiple stressors of small-holder agriculture.*

Stressors:	Source:
Population increase driving fragmentation of landholding	Various
Environmental degradation stemming variously from population, poverty, ill-defined property rights	Grimble et al., 2002
Regionalised and globalised markets, and regulatory regimes, increasingly concerned with issues of food quality and food safety	Reardon et al., 2003
Market failures interrupt input supply following withdrawal of government intervention	Kherallah et al., 2002
Continued protectionist agricultural policies in developed countries, and continued declines and unpredictability in the world prices of many major agricultural commodities of developing countries	Lipton, 2004, Various
Human immunodeficiency virus (HIV) and/or acquired immunodeficiency syndrome (AIDS) pandemic, particularly in Southern Africa, attacking agriculture through mass deaths of prime-age adults, which diverts labour resources to caring, erodes household assets, disrupts intergenerational transmission of agricultural knowledge, and reduces the capacity of agricultural service providers	Barnett and Whiteside, 2002
For pastoralists, encroachment on grazing lands and a failure to maintain traditional natural resource management	Blench, 2001
State fragility and armed conflict in some regions	Various

Adaptive capacity with respect to current climate is dynamic, and influenced by changes in wealth, human capital, information and technology, material resources and infrastructure, and 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 ENSO, but with some limitations (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 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).

Box 5.3. Climate change and the fisheries of the lower Mekong – an example of multiple stresses on a megadelta fisheries system due to human activity

Fisheries are central to the 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 People's Democratic Republic (PDR). There are approximately 1,000 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 Mtonnes (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 over-fishing) 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 to 41% in the basin and 16 to 19% in the delta (lower value is for years 2010 to 2138 and higher value for years 2070 to 2099, compared with 1961 to 1990 levels). Minimum monthly flows were estimated to decrease by 17 to 24% in the basin and 26 to 29% in the delta. Increased flooding would positively affect 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 the opposite effects on hydrology, namely marginally decreasing wet season flows and considerably increasing dry season flows (World Bank, 2004).

Models indicate that even a modest sea level rise of 20 cm 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.

Sub-Saharan Africa is one example of an 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 on 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 constrained by health status, lack of information and ineffective institutional structures, with potentially negative consequences for future adaptations to periods of heightened climate stress (see Chapter 9) (Reid and Vogel, 2006).

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

Declining global population growth (UN, 2004), rapidly rising urbanisation, shrinking shares of agriculture in the overall formation of incomes and fewer people dependent on agriculture are among the key factors likely to shape the social setting in which climate change is likely to evolve. These factors will determine how climate change affects agriculture, how rural populations can cope with changing climate conditions, and how these will affect food security. Any assessment of climate change impacts on agro-ecological conditions of agriculture must be undertaken against this background of changing socio-economic setting (Bruinsma, 2003).

5.3.1 Climate

Water balance and weather extremes are key to many agricultural and forestry impacts. Decreases in precipitation are predicted by more than 90% of climate model simulations by the end of the 21st century for the northern and southern sub-tropics (IPCC, 2007a). Increases in precipitation extremes are also very likely in the major agricultural production areas in Southern and Eastern Asia, in East Australia and in Northern Europe (Christensen et al., 2007). It should be noted that climate change impact models for food, feed and fibre do not yet include these recent findings on projected patterns of change in precipitation.

The current climate, soil and terrain suitability for a range of rain-fed crops and pasture types has been estimated by Fischer et al. (2002b) (see Figure 5.1a). 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., 2002b).

Changes in annual mean runoff are indicative of the mean water availability for vegetation. Projected changes between now and 2100 (see Chapter 3) show some consistent runoff patterns: increases in high latitudes and the wet tropics, and decreases in mid-latitudes and some parts of the dry tropics (Figure 5.1b). Declines in water availability are therefore projected to affect some of the areas currently suitable for rain-fed crops (e.g., in the Mediterranean basin, Central America and sub-tropical regions of Africa and Australia). Extreme increases in precipitation

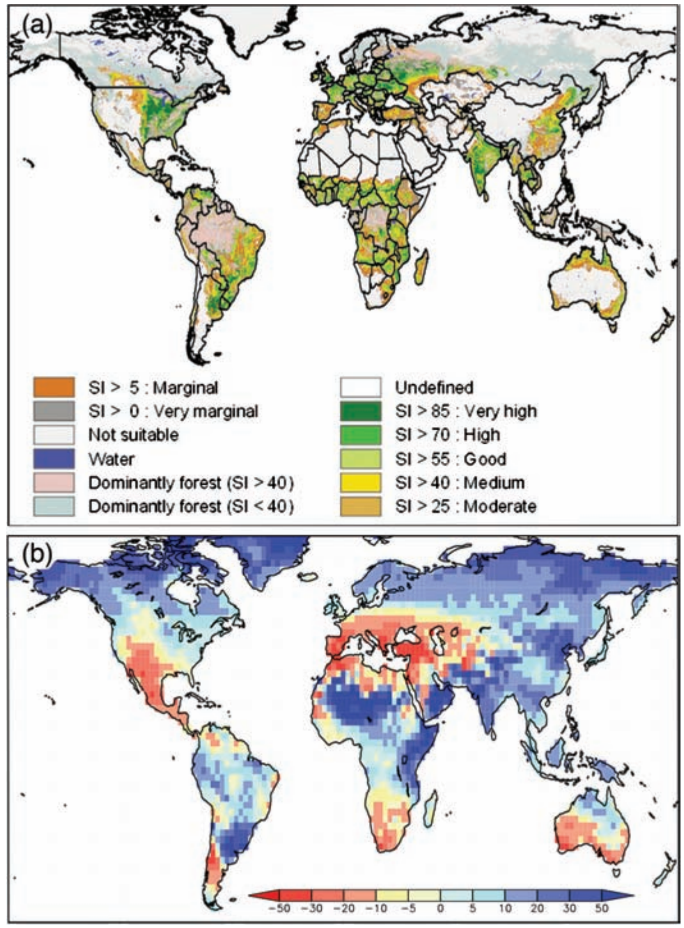

Figure 5.1. *(a) Current suitability for rain-fed crops (excluding forest ecosystems) (after Fischer et al., 2002b). SI = suitability index; (b) Ensemble mean percentage change of annual mean runoff between present (1981 to 2000) and 2100 (Nohara et al., 2006).*

(Christensen et al., 2007) also are very likely in major agricultural production areas (e.g., in Southern and Eastern Asia and in Northern Europe).

5.3.2 Balancing future global supply and demand in agriculture, forestry and fisheries

5.3.2.1 Agriculture

Slower population growth and an increasing proportion of better-fed people who require fewer additional calories are projected to lead to deceleration of global food demand. This slow-down in demand takes the present shift in global food consumption patterns from crop-based to livestock-based diets into account (Schmidhuber and Shetty, 2005). In parallel with the slow-down in demand, FAO (FAO, 2005a) expects growth in world agricultural production to decline from 2.2%/yr during the past 30 years to 1.6%/yr in 2000 to 2015, 1.3%/yr in 2015 to 2030 and 0.8%/yr in 2030 to 2050. This still implies a 55% increase in global crop production by 2030 and an 80% increase to 2050 (compared with 1999 to 2001). 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 agricultural land expansion will take place in developing countries with most of it occurring in sub-Saharan Africa and Latin America, which could result in direct trade-offs 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 currently to 3.8 tonnes/ha in 2050 (FAO, 2005a).

These improvements in the global supply-demand balance will be accompanied by a decline in the number of undernourished people from more than 800 million at present to about 300 million, or 4% of the population in developing countries, by 2050 (see Table 5.6) (FAO, 2005a). Notwithstanding these overall improvements, important food-security problems remain to be addressed at the local and national levels. Areas in sub-Saharan Africa, Asia and Latin America, with high rates of population growth and natural resource degradation, are likely to continue to have high rates of poverty and food insecurity (Alexandratos, 2005). Cassman et al. (2003) emphasise 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 on supply and demand of forestry products have been conducted in recent years (e.g., Sedjo and Lyon, 1990, 1996; FAO, 1998; Hagler, 1998; Sohngen et al., 1999, 2001). These studies project a shift in harvest from natural forests to plantations. For example, Hagler (1998) suggested the industrial wood harvest produced on plantations will increase from 20% of the total harvest in 2000 to more than 40% in 2030. Other estimates (FAO, 2004a) state that plantations produced about 34% of the total in 2001 and predict this portion may increase to 44% by 2020 (Carle et al., 2002) and 75% by 2050 (Sohngen et al., 2001). There will also be a global shift in the industrial wood supply from temperate to tropical zones and from the Northern to Southern Hemisphere. Trade in forest products will increase to balance the regional imbalances in demand and supply (Hagler, 1998).

Forecasts of industrial wood demand have tended to be consistently higher than actual demand (Sedjo and Lyon, 1990). Actual increases in demand have been relatively small (compare current demand of 1.6 billion m^3 with 1.5 billion m^3 in the early 1980s (FAO, 1982, 1986, 1988, 2005b)). The recent projections of the FAO (1997), Häggblom (2004), Sedjo and Lyon (1996) and Sohngen et al. (2001) forecast similar modest increases in demand to 1.8-1.9 billion m^3 by 2010 to 2015, in contrast to earlier higher predictions of 2.1 billion m^3 by 2015 and 2.7 billion m^3 by 2030 (Hagler, 1998). Similarly, an FAO (2001) study suggests that global fuelwood use has peaked at 1.9 billion 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 towards biofuels. Many other products and services depend on forest resources; however, there are no satisfactory estimates of the future global demand for 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 increase 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 fish production for food is forecast to increase from now to 2020, but not as rapidly as world demand. Per capita fish consumption and fish prices are expected to rise, with wide variations in 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%) and Latin America (84%), but not in India (45%) where aquaculture production will dominate (Delgado et al., 2003). All countries in Asia are likely to produce more fish between 2005 and 2020, but the rate of increase will taper. Trends in capture fisheries (usually zero growth or modest declines) will not unduly endanger overall fish supplies; however, any decline of fisheries is cause for concern given the projected growth in demand (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 in 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 and low levels of technology), and with uneven and unpredictable exposure to world markets. These systems have been characterised as 'complex, diverse and risk-prone' (Chambers et al., 1989). Risks (Scoones et al., 1996) 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 also practice hunting–gathering of wild resources to fulfil energy, clothing and health needs, as well as for direct food requirements. They participate in off-farm and/or non-farm employment (Ellis, 2000).

Subsistence and smallholder livelihood systems currently experience a number of interlocking stressors other than climate change and climate variability (outlined in Section 5.2.2). They also possess certain important resilience factors: efficiencies associated with the use of family labour (Lipton, 2004), livelihood diversity that allows the spreading of risks (Ellis, 2000) and indigenous knowledge that allows exploitation of risky environmental niches and coping with crises (see Cross Chapter Case Study on Indigenous Knowledge). The combinations of stressors and resilience factors give rise to complex positive and negative trends in livelihoods. Rural to urban migration will continue to be important, with urban populations expected to overtake rural populations in less developed regions by 2017 (UNDESA 2004). Within rural areas there will be continued diversification away from agriculture (Bryceson et al., 2000); 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.

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, and increased frequency of extreme events, 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 Effects of elevated CO_2 on plant growth and yield

Plant response to elevated CO_2 alone, without climate change, is positive and was reviewed extensively by the TAR. Recent studies confirm that the effects of elevated CO_2 on plant growth and yield will depend on photosynthetic pathway, species, growth stage and management regime, such as water and nitrogen (N) applications (Jablonski et al., 2002; Kimball et al., 2002; Norby et al., 2003; Ainsworth and Long, 2005). On average across several species and under unstressed conditions, recent data analyses find that, compared to current atmospheric CO_2 concentrations, crop yields increase at 550 ppm CO_2 in the range of 10-20% for C_3 crops and 0-10% for C_4 crops (Ainsworth et al., 2004; Gifford, 2004; Long et al., 2004). Increases in above-ground biomass at 550 ppm CO_2 for trees are in the range 0-30%, with the higher values observed in young trees and little to no response observed in mature natural forests (Nowak et al., 2004; Korner et al., 2005; Norby et al., 2005). Observed increase of above-ground production in C_3 pastures is about +10% (Nowak et al., 2004; Ainsworth and Long, 2005). For commercial forestry, slow-growing trees 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 (Calfapietra et al., 2003; Liberloo et al., 2005; Wittig et al., 2005). Norby et al. (2005) found a mean tree net primary production (NPP) response of 23% in young tree stands; however in mature tree stands Korner et al. (2005) reported no stimulation.

While some studies using re-analyses of recent FACE experimental results have argued that crop response to elevated CO_2 may be lower than previously thought, with consequences for crop modelling and projections of food supply (Long et al., 2005, 2006), others have suggested that these new analyses are, in fact, consistent with previous findings from both FACE and other experimental settings (Tubiello et al., 2007a, 2007b). In addition, simulations of unstressed plant growth and yield response to elevated CO_2 in the main crop-simulation models, including AFRC-Wheat, APSIM, CERES, CROPGRO, CropSyst, LINTULC and SIRIUS, have been shown to be in line with recent experimental data, projecting crop yield increases of about 5-20% at 550 ppm CO_2 (Tubiello et al., 2007b). Within that group, the main crop and pasture models, CENTURY and EPIC, project above-ground biomass production in C_3 species of about 15-20% at 550 ppm CO_2, i.e., at the high end of observed values for crops, and higher than recent observations for pasture. Forest models assume NPP increases at 550 ppm CO_2 in the range 15-30%, consistent with observed responses in young trees, but higher than observed for mature trees stands.

Importantly, plant physiologists and modellers alike recognise that the 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 (Tubiello and Ewert, 2002; Fuhrer, 2003; Karnosky, 2003; Gifford, 2004; Peng et al., 2004; Ziska and George, 2004; Ainsworth and Long, 2005; Tubiello et al., 2007a, 2007b). Assessment studies should therefore include these factors where possible, while analytical capabilities need to be enhanced. It is recommended that yield projections use a range of parameterisations of CO_2 effects to better convey the associated uncertainty range.

5.4.1.2 Interactions of elevated CO_2 with temperature and precipitation

Many recent studies confirm and extend the TAR findings that temperature and precipitation changes in future decades will modify, and often limit, direct CO_2 effects on plants. For instance, high temperature during flowering may lower CO_2 effects by reducing grain number, size and quality (Thomas et al., 2003; Baker, 2004; Caldwell et al., 2005). Increased temperatures may also reduce CO_2 effects indirectly, by increasing water demand. Rain-fed wheat grown at 450 ppm CO_2 demonstrated yield increases with temperature increases of up to 0.8°C, but declines with temperature increases beyond 1.5°C; 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 (Shaw et al., 2002; Zavaleta et al., 2003; Aranjuelo et al., 2005; Henry et al., 2005). Future CO_2 levels may favour C_3 plants over C_4 (Ziska, 2003), yet the opposite is expected under associated temperature increases; the net effects remain uncertain.

Importantly, climate impacts on crops may significantly depend on the precipitation scenario considered. In particular, since more than 80% of total agricultural land, and close to 100% of pasture land, is rain-fed, general circulation model (GCM) dependent changes in precipitation will often shape both the direction and magnitude of the overall impacts (Olesen and Bindi, 2002; Tubiello et al., 2002; Reilly et al., 2003). In general, changes in precipitation and, especially, in evaporation-precipitation ratios modify ecosystem function, particularly in marginal areas. Higher water-use efficiency and greater root densities under elevated CO_2 in field and forestry systems may, in some cases, alleviate drought pressures, yet their large-scale implications are not well understood (Schäfer et al., 2002; Wullschleger et al., 2002; Norby et al., 2004; Centritto, 2005).

5.4.1.3 Increased frequency of extreme events

The TAR has already reported on studies that document 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. Understanding links between increased frequency of extreme climate events and ecosystem disturbance (fires, pest outbreaks, etc.) is particularly important to quantify impacts (Volney and Fleming, 2000; Carroll et al., 2004; Hogg and Bernier, 2005). Although a few models since the TAR have started to incorporate effects of climate variability on plant production, most studies continue to include only effects on changes in mean variables.

5.4.1.4 Impacts on weed and insect pests, diseases and animal health

The importance of weeds and insect pests, and disease interactions with climate change, was reviewed in the TAR. New research confirms and extends these findings, including competition between C_3 and C_4 species (Ziska, 2003; Ziska and George, 2004). In particular, CO_2-temperature interactions are recognised as a key factor in determining plant damage from pests in future decades, though few quantitative analyses exist to date; CO_2-precipitation interactions will be likewise important (Stacey and Fellows, 2002; Chen et al., 2004; Salinari et al., 2006; Zvereva and Kozlov, 2006). Most studies continue to investigate pest damage as a separate function of either CO_2 (Chakraborty and Datta, 2003; Agrell et al., 2004; Chen et al., 2005a, 2005b) or temperature (Bale et al., 2002; Cocu et al., 2005; Salinari et al., 2006). For instance, recent warming trends in the U.S. and Canada have led to earlier spring activity of insects and proliferation of some species, such as the mountain pine beetle (Crozier and Dwyer, 2006; see also Chapter 1). Importantly, increased climate extremes may promote plant disease and pest outbreaks (Alig et al., 2004; Gan, 2004). Finally, new studies, since the TAR, are 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 Section 5.2). For instance, models project that bluetongue, which mostly affects sheep, and occasionally goat and deer, would spread from the tropics to mid-latitudes (Anon, 2006; van Wuijckhuise et al., 2006). Likewise, White et al. (2003) 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 combined.

5.4.1.5 Vulnerability of carbon pools

Impacts of climate change on managed systems, due to the large land area covered by forestry, pastures and crops, have the potential to affect the global terrestrial carbon sink and to further perturb atmospheric CO_2 concentrations (IPCC, 2001; Betts et al., 2004; Ciais et al., 2005). Furthermore, vulnerability of organic carbon pools to climate change has important repercussions for land sustainability and climate-mitigation actions. The TAR stressed that future changes in carbon stocks and net fluxes would critically depend on land-use planning (set aside policies, afforestation-reforestation, etc.) and management practices (such as N fertilisation, irrigation and tillage), in addition to plant response to elevated CO_2. Recent research confirms that carbon storage in soil organic matter is often increased under elevated CO_2 in the short-term (e.g., Allard et al., 2004); yet the total soil carbon sink may saturate at elevated CO_2 concentrations, especially when nutrient inputs are low (Gill et al., 2002; van Groenigen et al., 2006).

Uncertainty remains with respect to several key issues such as the impacts of increased frequency of extremes on the stability of carbon and soil organic matter pools; for instance, the recent European heatwave of 2003 led to significant soil carbon losses (Ciais et al., 2005). In addition, the effects of air pollution on plant function may indirectly affect carbon storage; recent research showed that tropospheric ozone results in significantly less enhancement of carbon-sequestration rates under elevated CO_2 (Loya et al., 2003), because of the negative effects of ozone on biomass productivity and changes in litter chemistry (Booker et al., 2005; Liu et al., 2005).

Within the limits of current uncertainties, recent modelling studies have investigated future trends in carbon storage over managed land by considering multiple interactions of climate and management variables. Smith et al. (2005) projected small overall carbon increases in managed land in Europe during this century due to climate change. By contrast, also including projected changes in land use resulted in small overall decreases. Felzer et al. (2005) projected increases in carbon storage on croplands globally under climate change up to 2100, but found that ozone damage to crops could significantly offset these gains.

Finally, recent studies show the importance of identifying potential synergies between land-based adaptation and mitigation strategies, linking issues of carbon sequestration, emissions of greenhouse gases, land-use change and long-term sustainability of production systems within coherent climate policy frameworks (e.g., Smith et al., 2005; Rosenzweig and Tubiello, 2007).

5.4.2 Food-crop farming, including tree crops

As noted in Section 5.1.3, the TAR indicated that impacts on food systems at the global scale might be small overall in the first half of the 21st century, but progressively negative after that. Importantly, crop production in (mainly low latitude) developing countries would suffer more, and earlier, than in (mainly mid- to high-latitude) developed countries, due to a combination of adverse agro-climatic, socio-economic and technological conditions (see recent analyses in Alexandratos, 2005).

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. These projections indicate potentially large negative impacts in developing regions, but only small changes in developed regions, which causes the globally aggregated impacts on world food production to be small (Fischer et al., 2002b, 2005b; Parry, 2004; Parry et al., 2005). Recent regional assessments have shown the high uncertainty that underlies such findings, and thus the possibility for surprises, by projecting, in some cases, significant negative impacts in key producing regions of developed countries, even before the middle of this century (Olesen and Bindi, 2002; Reilly et al., 2003). Many recent studies have contributed specific new knowledge with respect to several uncertainties and limiting factors at the time of the TAR, often highlighting the possibility for negative surprises, in addition to the impacts of mean climate change alone.

New Knowledge: *Increases in frequency of climate extremes may lower crop yields beyond the impacts of mean climate change.*

More frequent extreme events may lower long-term yields by directly damaging crops at specific developmental stages, such as temperature thresholds during flowering, or by making the timing of field applications more difficult, thus reducing the efficiency of farm inputs (e.g., Antle et al., 2004; Porter and Semenov, 2005). A number of simulation studies performed since the TAR have 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 would double in the U.S. by 2030 to US$3 billion/yr. Monirul and Mirza (2002) computed an increased risk of crop losses in Bangladesh from increased flood frequency under climate change. In scenarios with higher rainfall intensity, Nearing et al. (2004) projected increased risks of soil erosion, while van Ittersum et al. (2003) simulated higher risk of salinisation in arid and semi-arid regions, due to more water loss below the crop root zone. Howden et al. (2003) 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.

New Knowledge: *Impacts of climate change on irrigation water requirements may be large.*

Döll (2002) considered direct impacts of climate change on crop evaporative demand (no CO_2 effects) and computed increases in crop irrigation requirements of +5% to +8% globally by 2070, with larger regional signals (e.g., +15%) in South-East Asia, net of transpiration losses. Fischer et al. (2006) included positive CO_2 effects on crop water-use efficiency and computed increases in global net irrigation requirements of +20% by 2080, with larger impacts in developed versus developing regions, due to both increased evaporative demands and longer growing seasons under climate change. Fischer et al. (2006) and Arnell (2004) also projected increases in water stress (the ratio of irrigation withdrawals to renewable water resources) in the Middle East and South-East Asia. Recent regional studies have also found key climate change and water changes 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: *Stabilisation of CO_2 concentrations reduces damage to crop production in the long term.*

Recent work further investigated the effects of potential stabilisation of atmospheric CO_2 on regional and global crop production. Compared to the relatively small impacts of climate change on crop production by 2100 under business-as-usual scenarios, the impacts were only slightly less under 750 ppm CO_2 stabilization. However, stabilisation at 550 ppm CO_2 significantly reduced production loss (by -70% to –100%) and lowered risk of hunger (–60% to –85%) (Arnell et al., 2002; Tubiello and Fischer, 2006). These same studies suggested that climate mitigation may alter the regional and temporal mix of winners and losers with respect to business-as-usual scenarios, but concluded that specific projections are highly uncertain. In particular, in the first decades of this century and possibly up to 2050, some regions may be worse off with mitigation than without, due to lower CO_2 levels and thus reduced stimulation of crop yields (Tubiello and Fischer, 2006). Finally, a growing body of work has started to analyse potential relations between mitigation and adaptation (see Chapter 18).

TAR Confirmation: *Including effects of trade lowers regional and global impacts.*

Studies by Fischer et al. (2005a), Fischer et al. (2002a), Parry (2004) and Parry et al. (2005) confirm that including trade among world regions in assessment studies tends to reduce the overall projected impacts on agriculture compared to studies that lack an economic component. Yet, despite socio-economic development and trade effects, these and several other regional and global studies indicate that developing regions may be more negatively affected by climate change than other regions (Olesen and Bindi, 2002; Cassman et al., 2003; Reilly et al., 2003; Antle et al., 2004; Mendelsohn et al., 2004). Specific differences among studies depend significantly on factors such as projected population growth and food demand, as well as on trends in production technology and efficiency. In particular, the choice of the SRES scenario has as large an effect on projected global and regional levels of food demand and supply as climate change alone (Parry et al., 2004; Ewert et al., 2005; Fischer et al., 2005a; Tubiello et al., 2007a).

5.4.2.2 Review of crop impacts versus incremental temperature change

The increasing number of regional and global simulation studies performed since the TAR make it possible to produce synthesis graphs, showing not only changes in yield for key crops against temperature (a proxy for both time and severity of climate change), but also other important climate and management factors, such as changes in precipitation or adaptation strategies. An important limitation of these syntheses is that they collect single snapshots of future impacts, thereby lacking the temporal and causal dynamics that characterise actual responses in farmers' fields. Yet they are useful to summarise many independent studies.

Figure 5.2 provides an example of such analyses for temperature increases ranging from about 1-2ºC, typical of the next several decades, up to the 4-5°C projected for 2080 and beyond. The results of such simulations are generally highly uncertain due to many factors, including large discrepancies in GCM predictions of regional precipitation change, poor representation of impacts of extreme events and the assumed strength of CO_2 fertilisation (5.4.1). Nevertheless, these summaries indicate that in mid- to high-latitude regions, moderate to medium local increases in temperature (1ºC to 3ºC), across a range of CO_2 concentrations and rainfall changes, can have small beneficial impacts on the main cereal crops. Further warming has increasingly negative impacts (medium to low confidence) (Figure 5.2a, c, e). In low-latitude regions, these simulations indicate that even moderate temperature increases are likely to have negative yield impacts for major cereal crops (Figure 5.2b, d, f). For temperature increases more than 3°C, average impacts are stressful to all crops assessed and to all regions (medium to low confidence) (Figure 5.2). The low and mid-to-high latitude regions encompass the majority of global cereal production area. This suggests that global production potential, defined by Sivakumar and Valentin (1997) as equivalent to crop yield or Net Primary Productivity (NPP), is threatened at +1°C local temperature change and can accommodate no more that +3°C before beginning to decline. The studies summarised in Figure 5.2 also indicate that precipitation changes (and associated changes in precipitation:evaporation ratios), as well as CO_2 concentration, may critically shape crop-yield responses, over and above the temperature signal, in agreement with previous analyses (Section 5.4.1). The effects of adaptation shown in Figure 5.2 are considered in Section 5.5.

5.4.2.3 Research tasks not yet undertaken – ongoing uncertainties

Several uncertainties remain unresolved since the TAR. Better knowledge in several research areas is critical to improve our ability to predict the magnitude, and often even the direction, of future climate change impacts on crops, as well as to better define risk thresholds and the potential for surprises, at local, regional and global scales.

In terms of experimentation, there is still a lack of knowledge of CO_2 and climate responses for many crops other than cereals, including many of importance to the rural poor, such as root crops, millet, brassica, etc., with few exceptions, e.g., peanut (Varaprasad et al., 2003) and coconut (Dash et al., 2002). Importantly, 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 and a few studies have been published (Chakraborty and Datta, 2003; Runion, 2003; Salinari et al., 2006). Impacts of climate change alone on pest ranges and activity are also being increasingly analysed (e.g., Bale et al., 2002; Todd et al., 2002; Rafoss and Saethre, 2003; Cocu et al., 2005; Salinari et al., 2006). Finally, the true strength of the effect of elevated CO_2 on crop yields at field to regional scales, its interactions with higher temperatures and modified precipitation regimes, as well as the CO_2 levels beyond which saturation may occur, remain largely unknown.

In terms of modelling, 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 is important that uncertainties related to crop-model simulations of key processes, including their spatial-temporal resolution, be better evaluated, as findings of integrated studies will remain dependent upon the particular crop model used. It is still unclear how the implementation of plot-level experimental data on CO_2 responses compares across models; especially when simulations of several key limiting factors, such as soil and water quality, pests, weeds, diseases and the like, remain either unresolved experimentally or untested in models (Tubiello and Ewert, 2002). Finally, the TAR concluded that the economic, trade and technological assumptions used in many of the integrated assessment models to project food security under climate change were poorly tested against observed data. This remains the situation today (see also Section 5.6.5).

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 occur under most climates and range from extensive pastoral systems with grazing herbivores, to intensive systems based on forage and grain crops, where animals are mostly kept indoors. The 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 elevated CO_2 and climate change.*

Grasslands consisting of fast-growing, often short lived species, are sensitive to CO_2 and climate change, with the impacts 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 three years of experimental manipulation, plant diversity decreased with elevated CO_2 and nitrogen deposition, increased with elevated precipitation and showed no significant effect from warming (Zavaleta et al., 2003). Diversity responses to both single and combined global change treatments were driven mainly by significant gains and losses of forb[1] species (Zavaleta et al., 2003). Elevated CO_2 influences plant species

[1] Forb: a broad-leaved herb other than grass.

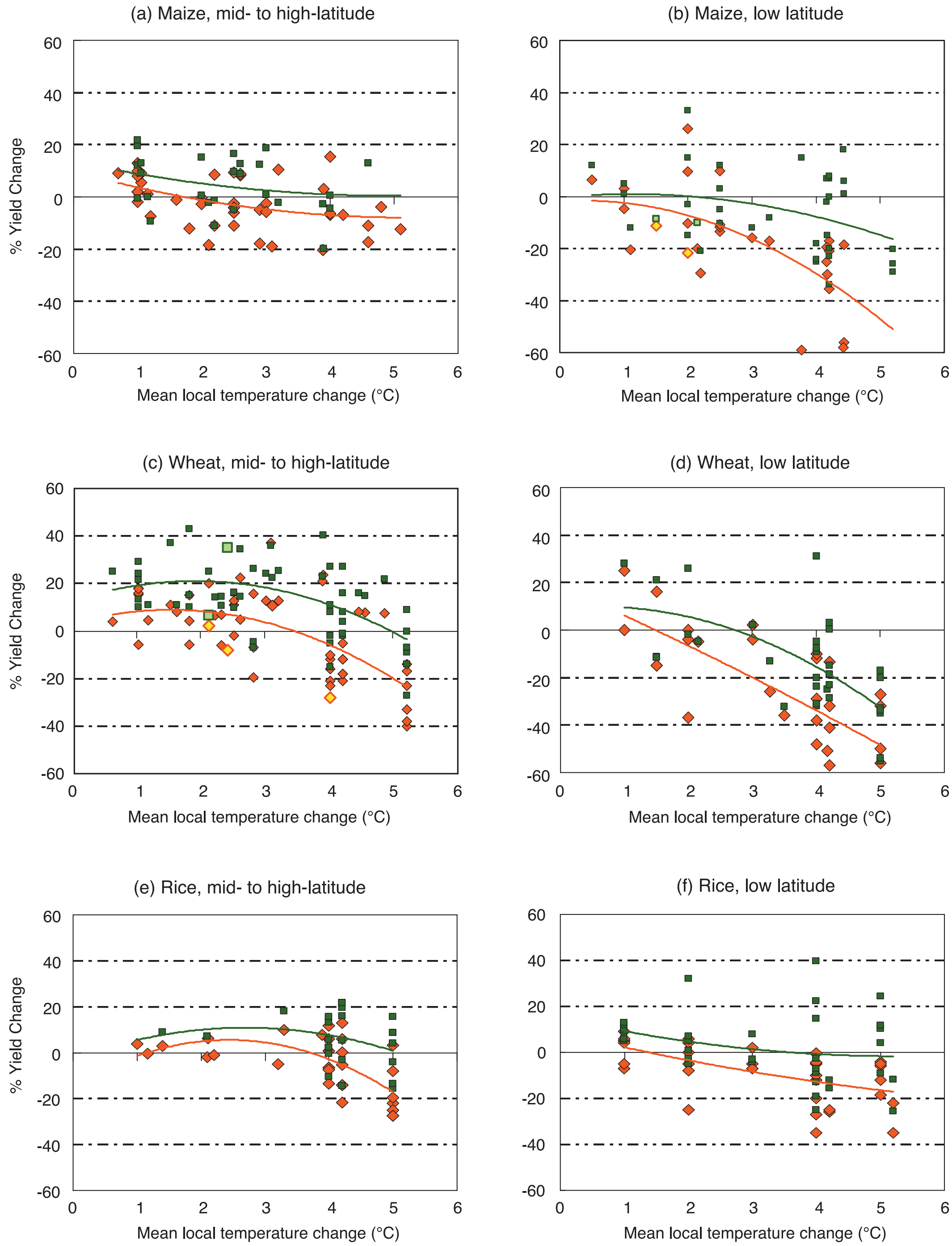

Figure 5.2. *Sensitivity of cereal yield to climate change for maize, wheat and rice, as derived from the results of 69 published studies at multiple simulation sites, against mean local temperature change used as a proxy to indicate magnitude of climate change in each study. Responses include cases without adaptation (red dots) and with adaptation (dark green dots). Adaptations+ represented in these studies include changes in planting, changes in cultivar, and shifts from rain-fed to irrigated conditions. Lines are best-fit polynomials and are used here as a way to summarise results across studies rather than as a predictive tool. The studies span a range of precipitation changes and CO_2 concentrations, and vary in how they represent future changes in climate variability. For instance, lighter-coloured dots in (b) and (c) represent responses of rain-fed crops under climate scenarios with decreased precipitation. Data sources: Bachelet and Gay, 1993; Rosenzweig and Parry, 1994; El-Shaer et al., 1997; Iglesias and Minguez, 1997; Kapetanaki and Rosenzweig, 1997; Matthews et al., 1997; Lal et al., 1998; Moya et al., 1998; Winters et al., 1998; Yates and Strzepek, 1998; Brown and Rosenberg, 1999; Evenson, 1999; Hulme et al., 1999; Parry et al., 1999; Iglesias et al., 2000; Saarikko, 2000; Tubiello et al., 2000; Bachelet et al., 2001; Easterling et al., 2001; Kumar and Parikh, 2001; Aggarwal and Mall, 2002; Alig et al., 2002; Arnell et al., 2002; Chang, 2002; Corobov, 2002; Cuculeanu et al., 2002; Mall and Aggarwal, 2002; Olesen and Bindi, 2002; Parry and Livermore, 2002; Southworth et al., 2002; Tol, 2002; Tubiello and Ewert, 2002; Aggarwal, 2003; Carbone et al., 2003; Chipanshi et al., 2003; Izaurralde et al., 2003; Jones and Thornton, 2003; Luo et al., 2003; Matthews and Wassmann, 2003; Reilly et al., 2003; Rosenberg et al., 2003; Tan and Shibasaki, 2003; Droogers, 2004; Faisal and Parveen, 2004; Adejuwon, 2005; Branco et al., 2005; Butt et al., 2005; Erda et al., 2005; Ewert et al., 2005; Fischer et al., 2005b; Gbetibouo and Hassan, 2005; Gregory et al., 2005; Haque and Burton, 2005; Maracchi et al., 2005; Motha and Baier, 2005; Palmer et al., 2005; Parry et al., 2005; Porter and Semenov, 2005; Sands and Edmonds, 2005; Schröter et al., 2005; Sivakumar et al., 2005; Slingo et al., 2005; Stigter et al., 2005; Thomson et al., 2005a, 2005b; Xiao et al., 2005; Zhang and Liu, 2005; Zhao et al., 2005; Aggarwal et al., 2006.*

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 confirmed (Luscher et al., 2005) and extended to temperate semi-natural grasslands using free air CO_2 enrichment (Teyssonneyre et al., 2002; Ross et al., 2004). 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 simulation of 1,350 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, such empirical model predictions have low confidence as they do not capture the complex interactions with management factors (e.g., grazing, cutting and fertiliser 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 (Milchunas et al., 2005). An increase in the legume content of swards may nevertheless compensate for the decline in protein content of the non-fixing plant species (Allard et al., 2003; Picon-Cochard et al., 2004). The decline under elevated CO_2 (Polley et al., 2003) of C_4 grasses, which are a less nutritious food resource than C_3 (Ehleringer et al., 2002), may also compensate for the reduced protein content under elevated CO_2. Yet the opposite is expected under associated temperature increases (see Section 5.4.1.2).

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 and 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 put a ceiling on dairy milk yield irrespective of feed intake. In the tropics, this ceiling reaches between half and 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°C and at high thermal heat index.

Production-response models for growing confined swine and beef cattle, and milk-producing dairy cattle, based on predicted climate outputs from GCM scenarios, have been developed by Frank et al. (2001). Across the entire USA, the percentage decrease in confined swine, beef and dairy milk production for the 2050 scenario averaged 1.2%, 2.0% and 2.2%, respectively, using the CGC (version 1) model and 0.9%, 0.7% and 2.1%, respectively, using the HadCM2 model.

New Knowledge: *Increased climate variability and droughts may lead to livestock loss.*

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 most often results in catastrophic losses in confined cattle feedlots (Hahn et al., 2001), with economic losses from reduced cattle performance exceeding those associated with cattle death losses by several-fold (Mader, 2003).

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 positive feedbacks between soil degradation and reduced vegetation and rainfall, with corresponding loss of pastoral areas and farmlands (Zheng et al., 2002).

A number of studies in Africa (see Table 5.3) 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. With increased heat stress in the future, water requirements for livestock will increase significantly compared with current conditions, so that overgrazing near watering points is likely to expand (Batima et al., 2005).

5.4.3.2 Impacts of gradual 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 IPCC (2007b) (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 Section 5.4.3.1).

Table 5.3 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. It should be noted that there are very few impact studies for tropical grasslands and rangelands.

5.4.4 Industrial crops and biofuels

Industrial crops include oilseeds, gums and resins, sweeteners, beverages, fibres, and medicinal and aromatic plants. There is practically no literature on the impact of climate change on gums and resins, and medicinal and aromatic plants. Limited new knowledge of climate change impacts on other industrial crops and biofuels has been developed since the TAR. Van Duivenbooden et al. (2002) used statistical models to estimate that rainfall reduction associated with climate change could reduce groundnut production in Niger, a large groundnut producing and exporting country, by 11-25%. Varaprasad et al. (2003) also concluded that groundnut yields would decrease under future warmer climates, particularly in regions where present temperatures are near or above optimum despite increased CO_2.

Impacts of climate change and elevated CO_2 on perennial industrial crops will be greater than on annual crops, as both damages (temperature stresses, pest outbreaks, increased damage from climate extremes) and benefits (extension of latitudinal optimal growing ranges) may accumulate with time (Rajagopal et al., 2002). For example, the cyclones that struck several states of India in 1952, 1955, 1996 and 1998 destroyed so many coconut palms that it will take years before production can be restored to pre-cyclone levels (Dash et al., 2002).

The TAR established large increases in cotton yields due to increases in ambient CO_2 concentration. Reddy et al. (2002), however, demonstrated that such increases in cotton yields were eliminated when changes in temperature and precipitation were also included in the simulations. Future climate change scenarios for the Mississippi Delta estimate a 9% mean loss in fibre yield. 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 IPCC, 2007c). Impacts of climate change on typical liquid biofuel crops such as maize and sorghum, and wood (solid biofuel) are discussed earlier in this chapter. Recent studies indicate that global warming may increase the yield potential of sugar beet, another important biofuel crop, in parts of Europe where drought is not a constraint (Jones et al., 2003; Richter et al., 2006). The annual variability of yields could, however, increase. 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 those of 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 will be similar to other regional crops.

5.4.5 Key future impacts on forestry

Forests cover almost 4 billion ha or 30% of land; 3.4 billion m^3 of wood were removed in 2004 from this area, 60% as industrial roundwood (FAO, 2005b). Intensively managed forest plantations comprised only 4% of the forest area in 2005, but their area is rapidly increasing (2.5 million ha annually (FAO, 2005b)). In 2000, these forests supplied about 35% of global roundwood;

Table 5.3. *Impacts on grasslands of incremental temperature change. (EXP = experiment; SIM = simulation without explicit reference to a SRES scenario; GMT = global mean temperature.)*

Local temperature change	Sub-sector	Region	Impact trends	Sign of impact	Scenario/Experiment	Source
+0-2°C	Pastures and livestock	Temperate	Alleviation of cold limitation increasing productivity Increased heat stress for livestock	+ -	SIM IS92a IS92a	Parsons et al., 2001 Riedo et al., 2001 Turnpenny et al., 2001
		Semi-arid and Mediterranean	No increase in net primary productivity	0	EXP	Shaw et al., 2002 Dukes et al., 2005
+3°C	Pastures and livestock	Temperate	Neutral to small positive effect (depending on GMT)	0 to +	SIM	Parsons et al., 2001 Riedo et al., 2001
		Temperate	Negative on swine and confined cattle	-	HadCM2 CGCM1	Frank and Dugas, 2001
		Semi-arid and Mediterranean	Productivity decline Reduced ewe weight and pasture growth More animal heat stress	- -	HadCM3 A2 and B2	Howden et al., 1999 Batima et al., 2005
		Tropical	No effect (no rainfall change assumed) More animal heat stress	- to 0 -	EXP	Newman et al., 2001 Volder et al., 2004

this share is expected to increase to 44% by 2020 (FAO, 2000). This section focuses on commercial forestry, including regional, national and global timber supply and demand, and associated changes in land-use, accessibility for harvesting and overall economic impacts. The ecosystem services of forests are reviewed in Chapter 4, while interactions with climate are discussed in IPCC (2007b). Key regional impacts are further detailed in Chapter 10, Section 10.4.4; Chapter 11, Section 11.4.4; Chapter 12, Section 12.4.4; Chapter 13, Section 13.4.1; and Chapter 14, Section 14.4.4. Finally, bioenergy is discussed in IPCC (2007c).

5.4.5.1 New findings since TAR

Confirmation of TAR: *Modelling studies predict increased global timber production.*

Simulations with yield models show that climate change can increase global timber production through location changes of forests and higher growth rates, especially when positive effects of elevated CO_2 concentration are taken into consideration (Irland et al., 2001; Sohngen et al., 2001; Alig et al., 2002; Solberg et al., 2003; Sohngen and Sedjo, 2005). For example, Sohngen et al. (2001) and Sohngen and Sedjo (2005) projected a moderate increase of timber yield due to both rising NPP and a poleward shift of the most productive species due to climate change. Changing timber supply will affect the market and could impact supply for other uses, e.g., for biomass energy. Global economic impact assessments predict overall demand for timber production to increase only modestly (see Section 5.3.2.2) with a moderate increase or decrease of wood prices in the future in the order of up to ±20% (Irland et al., 2001; Sohngen et al., 2001; Nabuurs et al., 2002; Perez-Garcia et al., 2002; Solberg et al., 2003; Sohngen and Sedjo, 2005), with benefits of higher production mainly going to consumers. For the U.S., Alig et al. (2002) computed that the net impact of climate change on the forestry sector may be small. Similarly, Shugart et al. (2003) concluded that the U.S. 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 summarised in Table 5.4.

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 will exhibit large variability, similar to that discussed for crops. Mendelsohn (2003), analysing production in California, projected that, at first (2020s), climate change increases harvests by

Table 5.4. *Examples of simulated climate change impacts on forestry.*

Reference; *location*	Scenario and GCM	Production impact	Economic impact
Sohngen et al., 2001; Sohngen and Sedjo, 2005. *Global*	UIUC and Hamburg T-106 for CO_2 topping 550 ppm in 2060	• 2045: production up by 29-38%; reductions in N. America, Russia; increases in S. America and Oceania. • 2145: production up by 30%, increases in N. America, S. America, and Russia.	• 2045: prices reduced, high-latitude loss, low-latitudes gain. • 2145: prices increase up to 80% (no climate change), 50% (with climate change), high-latitude gain, low-latitude loss. Benefits go to consumers.
Solberg et al., 2003. *Europe*	Baseline, 20-40%, increase in forest growth by 2020	• Increased production in W. Europe, • Decreased production in E. Europe.	Price drop with an increase in welfare to producers and consumers. Increased profits of forest industry and forest owners.
Perez-Garcia et al., 2002. *Global*	TEM & CGTM MIT GCM, MIT EPPA emissions	• Harvest increase in the US West (+2 to +11%), New Zealand (+10 to +12%), and S. America (+10 to +13%). • Harvest decrease in Canada.	Demand satisfied; prices drop with an increase in welfare to producers and consumers.
Lee and Lyon, 2004. *Global*	ECHAM-3 (2 × CO_2 in 2060), TSM 2000, BIOME 3, Hamburg model	• 2080s, no climate change: increase of the industrial timber harvest by 65% (normal demand) or 150% (high demand); emerging regions triple their production. • With climate change: increase of the industrial timber harvest by 25% (normal demand) or 56% (high demand), E. Siberia & US South dominate production.	No climate change: • Pulpwood price increases 44% • Solid wood increase 21%. With climate change: • Pulpwood price decrease 25% • Solid wood decrease 34% • Global welfare 4.8% higher than in no climate change scenario.
Nabuurs et al., 2002. *Europe*	HadCM2 under IS92a 1990-2050	18% extra increase in annual stemwood increment by 2030, slowing down on a longer term.	Both decreases or increases in prices are possible.
Schroeter, 2004. *Europe*	IPCC A1FI, A2, B1, B2 up to 2100. Few management scenarios	• Increased forest growth (especially in N. Europe) and stocks, except for A1FI. • 60-80% of stock change is due to management, climate explains 10-30% and the rest is due to land use change.	In the A1FI and A2 scenarios, wood demand exceeds potential felling, particularly in the second half of the 21st century, while in the B1 and B2 scenarios future wood demand can be satisfied.
Alig et al., 2002; Joyce et al., 2001. *USA*	CGCM1+TEM HadCM2+TEM CGCM1+VEMAP HadCM2+VEMAP IS92a	• Increase in timber inventory by 12% (mid-term); 24% (long-term) and small increase in harvest. Major shift in species and an increase in burnt area by 25-50%. • Generally, high elevation and northern forests decline, southern forests expand.	• Reduction in log prices • Producer welfare reduced compared to no climate change scenario • Lower prices; consumers will gain and forest owners will lose

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 will also substantially impact other services, such as seeds, nuts, hunting, resins, plants used in pharmaceutical and botanical medicine, and in the cosmetics industry; these impacts will also be highly diverse and regionalised.

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 may be revised to lower values than previously assumed in forest growth models. A number of FACE studies in 550 ppm CO_2 showed average NPP increase of 23% in young tree stands (Norby et al., 2005). However, in a 100-year old tree stand, Korner et al. (2005) found little overall stimulation in stem growth over a period of four years. Additionally, the initial increase in growth increments may be limited by competition, disturbance, air pollutants, nutrient limitations and other factors (Karnosky, 2003), and the response is site- and species-specific. By contrast, models often presume larger fertilisation effects: Sohngen et al. (2001) assumed a 35% NPP increase under a $2 \times CO_2$ scenario. Boisvenue and Running (2006) suggest increasing forest-growth rate due to increasing CO_2 since the middle of the 20th century; however, some of this increase may result from other effects, such as land-use change (Caspersen et al., 2000).

In spite of improvements in forest modelling, model limitations persist. Most of the major forestry models don't include key ecological processes. Development of Dynamic Global Vegetation Models (DGVMs), which are spatially explicit and dynamic, will allow better predictions of climate-induced vegetative changes (Peng, 2000; Bachelet et al., 2001; Cramer et al., 2001; Brovkin, 2002; Moorcroft, 2003; Sitch et al., 2003) by simulating the composition of deciduous and evergreen trees, forest biomass, production, and water and nutrient cycling, as well as fire effects. DGVMs are also able to provide GCMs with feedbacks from changing vegetation, e.g., Cox et al. (2004) found that DGVM feedbacks raise HadCM3LC GCM temperature and decrease precipitation forecasts for Amazonia, leading to eventual loss of rainforests. There are still inconsistencies, however, between the models used by ecologists to estimate the effects of climate change on forest production and composition and those used to predict forest yield. Future development of the models that integrate both the NPP and forestry yield approaches (Nabuurs et al., 2002; Peng et al., 2002) will significantly improve the predictions.

5.4.5.2 Additional factors not included in the models contribute uncertainty

Fire, insects and extreme events are not well modelled. 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; Podur et al., 2002; Bergeron et al., 2004; Girardin et al., 2004; Mouillot and Field, 2005), with some of the changes linked to climate change (Gillett et al., 2004; Westerling et al., 2006). Climate change will interact with fuel type, ignition source and topography in determining future damage risks to the forest industry, especially for paper and pulp operations; fire hazards will also pose health threats (see Chapter 8, Section 8.2) and affect landscape recreational value. There is an uncertainty associated with many studies of climate change and forest fires (Shugart et al., 2003; Lemmen and Warren, 2004); however, current modelling studies suggest that increased temperatures and longer growing seasons will elevate fire risk in connection with increased aridity (Williams et al., 2001; Flannigan et al., 2005; Schlyter et al., 2006). For example, Crozier and Dwyer (2006) 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 et al. (2005) projected as much as 74-118% increase of the area burned in Canada by the end of the 21st century under a $3 \times CO_2$ scenario. However, much of this fire increase is expected in inaccessible boreal forest regions, so the effects of climate-induced wildfires on timber production may be more modest.

For many forest types, forest health questions are of great concern, with pest and disease outbreaks as major sources of natural disturbance. The effects vary from defoliation and growth loss to timber damage to massive forest die backs; it is very likely that these natural disturbances will be altered by climate change and will have an impact on forestry (Alig et al., 2004). Warmer temperatures have already enhanced the opportunities for insect spread across the landscape (Carroll et al., 2004; Crozier and Dwyer, 2006). Climate change can shift the current boundaries of insects and pathogens and modify tree physiology and tree defence. Modelling of climate change impacts on insect and pathogen outbreaks remains limited.

The effects of climate extremes on commercial forestry are region-specific and include reduced access to forestland, increased costs for road and facility maintenance, direct damage to trees by wind, snow, frost or ice; indirect damage from higher risks of wildfires and insect outbreaks, effects of wetter winters and early thaws on logging, etc. For example, in January 2005 Hurricane Gudrun, with maximum gusts of 43 m/s, damaged more than 60 million m^3 of timber in Sweden, reducing the country's log trade deficit by 30% (UNECE, 2006). Higher direct and indirect risks could affect timber supplies, market prices and cost of insurance (DeWalle et al., 2003). Globally, model predictions mentioned in the SAR suggested extensive forest die back and composition change; however, some of these effects may be mitigated (Shugart et al., 2003) and changes in forest composition will likely occur gradually (Hanson and Weltzin, 2000).

Interaction between multiple disturbances is very important for understanding climate change impacts on forestry. Wind events can damage trees through branch breaking, crown loss, trunk breakage or complete stand destruction. The damage might increase for faster-growing forests. This damage can be further aggravated by increased damage from insect outbreaks and wildfires (Fleming et al., 2002; Nabuurs et al., 2002). Severe drought increases mortality and is often combined with insect and pathogen damage and wildfires. For example, a positive feedback between deforestation, forest fragmentation, wildfire and increased frequency of droughts appears to exist in the Amazon basin, so that a warmer and drier regional climate may trigger massive deforestation (Laurance and Williamson, 2001; Laurance et al., 2004; Nepstad et al., 2004). Few, if any, models can simulate these effects.

5.4.5.3 Social and economic impacts

Climate change impacts on forestry and a shift in production preferences (e.g., towards biofuels) will translate into social and economic impacts through the relocation of forest economic activity. Distributional effects would involve businesses, landowners, workers, consumers, governments and tourism, with some groups and regions benefiting while others experience losses. Net benefits will accrue to regions that experience increased forest production, while regions with declining activity will likely face net losses. If wood prices decline, as most models predict, consumers will experience net benefits, while producers experience net losses. Even though the overall economic benefits are likely to exceed losses, the loss of forest resources may directly affect 90% of the 1.2 billion forest-dependent people who live in extreme poverty (FAO, 2004a). Although forest-based communities in developing countries are likely to have modest impact on global wood production, they may be especially vulnerable because of the limited ability of rural, resource-dependent communities to respond to risk in a proactive manner (Davidson et al., 2003; Lawrence, 2003). Non-timber forest products (NTFP) such as fuel, forest foods or medicinal plants, are equally important for the livelihood of the rural communities. In many rural Sub-Saharan Africa communities, NTFP may supply over 50% of a farmer's cash income and provide the health needs for over 80% of the population (FAO, 2004a). Yet little is known about the possible impacts on NFTP.

5.4.6 Capture fisheries and aquaculture: marine and inland waters

World capture production of fish, crustaceans and molluscs in 2004 was more than twice that of aquaculture (Table 5.5), but since 1997 capture production decreased by 1%, whereas aquaculture increased by 59%. By 2030, capture production and aquaculture are projected to be closer to equality (93 Mt and 83 Mt, respectively) (FAO, 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.

Some aquaculture, particularly of plants and molluscs, depends on naturally occurring nutrients and production, but the rearing of fish and Crustacea usually requires the 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).

For aquatic systems we still lack the kind of experimental data and models used to predict agricultural crop yields under different climate scenarios; therefore, it is not possible to provide quantitative predictions such as are available for other sectors.

Table 5.5. *World fisheries production in 2004 (source: FAO, Yearbook of Fisheries Statistics http://www.fao.org/fi/statist/statist.asp).*

World production in Mt		Inland	Marine	Total
Capture production	Fish, crustaceans, molluscs, etc.	8.8	85.8	94.6
Aquaculture production	Fish, crustaceans, molluscs, etc.	27.2	18.3	45.5
	Aquatic plants	0.0	13.9	13.9

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 increased acidity (lower 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; and (vi) uncertain future supply of fishmeal and oils from capture fisheries. Positive impacts include increased growth rates and food conversion efficiencies, increased length of growing season, range expansion and use of new areas due to decrease in ice cover.

Information from experimental, observational and modelling studies conducted since the TAR supports these conclusions and provides more detail, especially concerning regional effects.

5.4.6.2 What is new since the TAR?

New Knowledge: *Effects of temperature on fish growth*.

One experimental study showed positive effects for rainbow trout (*Oncorhyncus mykiss*) on appetite, growth, protein synthesis and oxygen consumption with a 2°C temperature increase in winter, but negative effects with the same increase in summer. Thus, temperature increases may cause seasonal increases in growth, but also risks to fish populations at 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 are speculative and complex (Morgan et al., 2001).

New Knowledge: *Current and future direct effects*.

Direct effects of increasing temperature on marine and freshwater ecosystems are already evident, with rapid poleward shifts in regions, such as the north-east Atlantic, where temperature change has been rapid (see Chapter 1). 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[2], e.g., salmon (Friedland et al., 2003) and sturgeon (Reynolds et al., 2005).

New Knowledge: *Current and future effects via the food chain*.

Changes in primary production and transfer through the food chain due to climate will have a key impact on fisheries. Such

[2] Diadromous: migrating between fresh and salt water.

changes may be either positive or negative and the aggregate impact at global level is unknown. Evidence from the Pacific and the Atlantic suggests that nutrient supply to the upper productive layer of the ocean is declining due to reductions in the Meridional Overturning Circulation and upwelling (McPhaden and Zhang, 2002; Curry and Mauritzen, 2005) and changes in the deposition of wind-borne nutrients. This has resulted in reductions in primary production (Gregg et al., 2003), but with considerable regional variability (Lehodey et al., 2003). Further, the decline in pelagic fish catches in Lake Tanganyika since the late 1970s has been ascribed to climate-induced increases in vertical stability of the water column, resulting in reduced availability of nutrients (O'Reilly et al., 2004).

Coupled simulations, using six different models to determine the ocean biological response to climate warming between the beginning of the industrial revolution and 2050 (Sarmiento et al., 2004), showed 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.

New Knowledge: *Current and future effects of spread of pathogens.*

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) (see Box 5.4). 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 multinucleated sphere X (MSX) disease caused by *P. marinus* (Hofmann et al., 2001). The poleward spread of this and other pathogens is expected to continue as winter temperatures warm.

New Knowledge: *Economic impacts.*

A recent modelling study predicts that, for the fisheries sector, climate change will have the greatest impact on the economies of central and northern Asian countries, the western Sahel and 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 (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 sub-tropical 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 that incorporates 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, 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 'regime shifts' (fairly abrupt changes in both physics and biology persisting for up to a decade). These changes have major consequences for the productivity and species composition of fisheries resources in the region (King, 2005).

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

Climate-related reductions in production cause fish stocks to decline at previously sustainable levels of fishing; 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 (Spalding and Jarvis, 2002; Grandcourt and Cesar, 2003). In the longer term, there may be serious consequences for fisheries production that result from loss of coral communities and reduced structural complexity, which result in reduced fish species richness, local extinctions and loss of species within key functional groups of reef fish (Sano, 2004; Graham et al., 2006).

5.4.7 Rural livelihoods: subsistence and smallholder agriculture

The impacts of climate change on subsistence and smallholder agriculture, pastoralism and artisanal fisheries were not discussed explicitly in the TAR, though discussion of these systems is implicit in various sections. A number of case studies of impacts on smallholder livelihood systems in developing countries are beginning to appear, some focussed on recent and current climate variability seen within a climate change context (Thomas et al., 2005a), others using modelling approaches to examine future impacts on key smallholder crops (Abou-Hadid, 2006; Adejuwon, 2006) or ecosystems used by smallholder farmers (Lasco and Boer, 2006). In some cases impacts are discussed within work focussed more on adaptation (Thomas et al., 2005a).

Specific impacts must be examined within the context of whole sets of confounding impacts at regional to local scales (Adger et al., 2003). It is difficult to ascribe levels of confidence to these confounding impacts because livelihood systems are typically complex and involve a number of crop and livestock species, between which there are interactions (for example, intercropping practices (Richards, 1986) or the use of draught-animal power for cultivation (Powell et al., 1998)), and potential substitutions such as alternative crops. Many smallholder livelihoods will also include elements such as use of wild resources, and non-agricultural strategies such as use of remittances. Coping strategies for extreme climatic events such as drought (Davies, 1996; Swearingen and Bencherifa, 2000; Mortimore and Adams, 2001; Ziervogel, 2003) typically involve changes in the relative importance of such elements, and in the interactions between them. Pastoralist coping strategies in northern Kenya and southern Ethiopia are discussed in Box 5.5.

Impacts of climate change upon these systems will include:

- The direct impacts of changes in temperature, CO_2 and precipitation on yields of specific food and cash crops, productivity of livestock and fisheries systems, and animal health, 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 medium-term (to 2025) (Corbera et al., 2006). 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) decreased water supply from snowcaps for major smallholder irrigation systems, particularly in the Indo-Gangetic plain (Barnett et al., 2005), (ii) the effects of sea level rise on coastal areas, (iii) increased frequency of landfall tropical storms (Adger, 1999) and (iv) other forms of environmental impact still being identified, such as increased forest-fire risk (Agrawala et al., 2003, for the Mount Kilimanjaro ecosystem) and remobilisation of dunes (Thomas et al., 2005b for semi-arid Southern Africa).
- Impacts on human health, like malaria risk (see Chapter 8, Section 8.4.1.2), affect labour available for agriculture and other non-farm rural economic activities, such as tourism (see Chapter 7, Section 7.4.2.2).

For climate change impacts on the three major cereal crops grown by smallholders, we refer to Figure 5.2a-f and discussion in Sections 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

Box 5.5. Pastoralist coping strategies in northern Kenya and southern Ethiopia

African pastoralism has evolved in adaptation to harsh environments with very high spatial and temporal variability of rainfall (Ellis, 1995). Several recent studies (Ndikumana et al., 2000; Hendy and Morton, 2001; Oba, 2001; McPeak and Barrett, 2001; Morton, 2006) have focussed on the coping strategies used by pastoralists during recent droughts in northern Kenya and southern Ethiopia, and the longer-term adaptations that underlie them:

- *Mobility* remains the most important pastoralist adaptation to spatial and temporal variations in rainfall, and in drought years many communities make use of fall-back grazing areas unused in 'normal' dry seasons because of distance, land tenure constraints, animal disease problems or conflict. But encroachment on and individuation of communal grazing lands, and the desire to settle to access human services and food aid, have severely limited pastoral mobility.
- Pastoralists engage in *herd accumulation* and most evidence now suggests that this is a rational form of insurance against drought.
- A small proportion of pastoralists now hold some of their wealth in bank accounts, and others use informal savings and credit mechanisms through shopkeepers.
- Pastoralists also use *supplementary feed* for livestock, purchased or lopped from trees, as a coping strategy; they intensify *animal disease management* through indigenous and scientific techniques; they pay for *access to water* from powered boreholes.
- *Livelihood diversification* away from pastoralism in this region predominantly takes the form of shifts into low-income or environmentally unsustainable occupations such as charcoal production, rather than an adaptive strategy to reduce *ex-ante* vulnerability.
- A number of *intra-community mechanisms* distribute both livestock products and the use of live animals to the destitute, but these appear to be breaking down because of the high levels of covariate risk within communities.

frequency of extreme events on yields (see also Porter and Semenov, 2005). Burke et al. (2006) demonstrate the risk of widespread drought in many regions, including Africa. Projected impacts on world regions, some of which are disaggregated into smallholder and subsistence farmers or similar categories, are reviewed in the respective regional chapters. An important study by Jones and Thornton (2003) found that aggregate yields of smallholder rain-fed maize in Africa and Latin America are likely to decrease by almost 10% by 2055, but these results hide enormous regional variability (see also Fischer et al., 2002b) of concern for subsistence agriculture.

With a large body of smallholder and subsistence farming households in the dryland tropics, there is especial concern over temperature-induced declines in crop yields, and increasing frequency and severity of drought. These will lead to the following generalisations (low confidence):

- increased likelihood of crop failure;
- increased diseases and mortality of livestock and/or forced sales of livestock at disadvantageous prices (Morton and de Haan, 2006);
- 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 combine with non-climate stressors as listed in Section 5.2.2 above, including the impacts of globalisation (O'Brien and Leichenko, 2000) and HIV and/or AIDS (Gommes et al., 2004; see also Chapter 8).

Modelling studies are needed to understand the interactions between these different forms of climate change impacts and the adaptations they will require. The multi-agent modelling of Bharwani et al. (2005) is one possible approach. Empirical research on how current strategies to cope with extreme events foster or constrain longer-term adaptation is also important (see Davies, 1996). Knowledge of crop responses to climate change also needs to be extended to more crops of interest to smallholders.

Many of the regions characterised by subsistence and smallholder agriculture are storehouses of unexplored biodiversity (Hannah et al., 2002). Pressure to cultivate marginal land or to adopt unsustainable cultivation practices as yields drop, and the break down of food systems more generally (Hannah et al., 2002), may endanger biodiversity of both wild and domestic species. Smallholder and subsistence farming areas are often also environmentally marginal (which does not necessarily conflict with biodiversity) and at risk of land degradation as a result of climate trends, but mediated by farming and livestock-production systems (Dregne, 2000).

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 (see Chapter 17). Adaptations are divided here into two categories: *autonomous adaptation*, which is the ongoing implementation of existing knowledge and technology in response to the changes in climate experienced, and *planned adaptation*, which is the increase in adaptive capacity by mobilising institutions and policies to establish or strengthen conditions favourable for effective adaptation and investment in new technologies and infrastructure.

The TAR noted agriculture has historically shown high levels of adaptability to climate variations and that while 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., Parson et al., 2003).

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 (Aggarwal and Mall, 2002; Alexandrov et al., 2002; Tubiello et al., 2002; Adams et al., 2003; Easterling et al., 2003; Howden et al., 2003; Howden and Jones, 2004; Butt et al., 2005; Travasso et al., 2006; Challinor et al., 2007). These adaptations include:

- altering inputs such as varieties and/or 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 climate and altering amounts and timing of irrigation and other water management practices;
- wider use of technologies to 'harvest' water, conserve soil moisture (e.g., crop residue retention) and to use water more effectively in areas with rainfall decreases;
- water management to prevent waterlogging, erosion and nutrient leaching in areas with rainfall increases;
- altering the timing or location of cropping activities;
- diversifying income by integrating other farming activities such as livestock raising;
- improving the effectiveness of pest, disease and weed management practices through wider use of integrated pest and pathogen management, development and use of varieties and species resistant to pests and diseases, maintaining or improving quarantine capabilities, and 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 a modelling study for 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%; Tubiello et al., 2000). We have synthesised results from many crop adaptation studies for wheat, rice and maize (Figure 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 when compared with yields when no adaptation is used. Another way to view 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°C in tropical regions and 4.5 to 5°C in temperate regions. Further warming than these ranges in either region exceeds adaptive capacity. The benefits of autonomous adaptations tend to level off with increasing temperature changes (Howden and Crimp, 2005) while potential negative impacts increase.

While autonomous adaptations such as the above have the potential for considerable damage avoidance from problematic climate changes, there has been little evaluation of how effective and widely adopted these adaptations may actually be, given (i) the complex nature of farm decision-making in which there are many non-climatic issues to manage, (ii) the likely diversity of responses within and between regions in part due to possible differences in climate changes, (iii) the difficulties that might arise if climate changes are non-linear or increase climate extremes, (iv) time-lags in responses and (v) 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 and/or herding communities is generally considered to be very low (Leary et al., 2006). These considerations also apply to the livestock, forestry and fisheries.

Adaptations in field-based livestock include matching stocking rates with pasture production, rotating pastures, modifying grazing times, altering forage and animal species/breeds, altering the integration of mixed livestock/crop systems, including the use of adapted forage crops, re-assessing fertiliser applications, ensuring adequate water supplies and using supplementary feeds and concentrates (Daepp et al., 2001; Holden and Brereton, 2002; Adger et al., 2003; Batima et al., 2005). 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. Following from the above, in intensive livestock industries, there may be reduced need for winter housing and for feed concentrates in cold climates, 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.

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 minimise fire and insect damage, adjusting to altered wood size and quality, and adjusting fire-management systems (Sohngen et al., 2001; Alig et al., 2002; Spittlehouse and Stewart, 2003; Weih, 2004). Adaptation strategies to control insect damage can include prescribed burning to reduce forest vulnerability to increased insect outbreaks, non-chemical insect control (e.g., baculoviruses) and adjusting harvesting schedules, so that those stands most vulnerable to insect defoliation can 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), which limits adaptation opportunities. Even in more intensively managed forests where adaptation activities may be more feasible (Shugart et al., 2003) the long time-lags between planting and harvesting trees will complicate 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, which 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 of natural fish populations, which are common-property resources, precludes the kind of management adaptations to climate change suggested for the crop, livestock and forest sectors. Adaptation options thus centre on 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 levels 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 use of natural resource systems, migrations can impede economic development (Allison et al., 2005; see Chapter 17, Box 17.8).

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 policy-based adaptation to climate change have been identified for agriculture, forests and fisheries (Howden et al., 2003; Kurukulasuriya and Rosenthal, 2003;

Aggarwal et al., 2004; Antle et al., 2004; Easterling et al., 2004). 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, autonomous adaptation activities occur (see Chapter 17). Effective planning and capacity building for adaptation to climate change could include:

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). 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 the surveillance of pests, diseases and other factors directly affected by climate.
2. Managers need to be confident that the projected changes will significantly impact on their enterprise (Burton and Lim, 2005). This could be assisted by policies that support the research, systems analysis, extension capacity, and industry and regional networks that provide this information.
3. There needs to be technical and other options available to respond to the projected changes. Where the existing technical options are inadequate to respond, investment in new technical or management options may be required (e.g., improved crop, forage, livestock, forest and fisheries germplasm, including via biotechnology, see Box 5.6) or old technologies revived in response to the new conditions (Bass, 2005).
4. Where there are major land use changes, industry location changes and migration, there may be a role for governments to support these transitions via direct financial and material support, creating alternative livelihood options. These include 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 and 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. Developing new infrastructure, policies and institutions to support the new management and land use arrangements by 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, 2003a); establishment of accessible, efficiently functioning markets for products and inputs (seed, fertiliser, labour, etc.) and for financial services, including insurance (Turvey, 2001).
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 policy-based 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, among many others: the 'mainstreaming' of climate change adaptation into policies intended to enhance broad resilience (see Chapter 17).

5.6 Costs and other socio-economic aspects, including food supply and security

5.6.1 Global costs to agriculture

Fischer et al. (2002b) quantify the impact of climate change on global agricultural GDP by 2080 as between -1.5% and +2.6%, with considerable regional variation. Overall, mid- to high-latitudes agriculture stands to benefit, while agriculture in low latitudes will be adversely affected. However, Fischer et al. (2002b) suggest that, taking into account economic adjustment,

Box 5.6. 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 to drought and temperature. A number of studies have demonstrated genetic modifications to major crop species (e.g., maize and soybeans) that increased their water-deficit tolerance (as reviewed by Drennen et al., 1993; Kishor et al., 1995; Pilon-Smits et al., 1995; Cheikh et al., 2000), although this may not extend to the wider range of crop plants. Similarly, there are possibilities for enhanced resistance to pests and diseases, salinity and waterlogging, or for opportunities such as change in flowering times or enhanced responses to elevated CO_2. 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 is often compensated or dampened so that little change in plant growth and yield is achieved from the 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 (2004b) argue that it will be a crucial adjunct to conventional breeding (it is likely that both will be needed to meet future environmental challenges, including climate change).

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 summarised in Figure 5.3. Overall, the effects of higher global mean temperatures (GMTs) on food prices follow the expected changes in crop and livestock production. Higher output associated with a moderate increase in the GMT likely results in a small decline in real world food (cereals) prices, while GMT changes in the range of 5.5°C or more could lead to a pronounced increase in food prices of, on average, 30%.

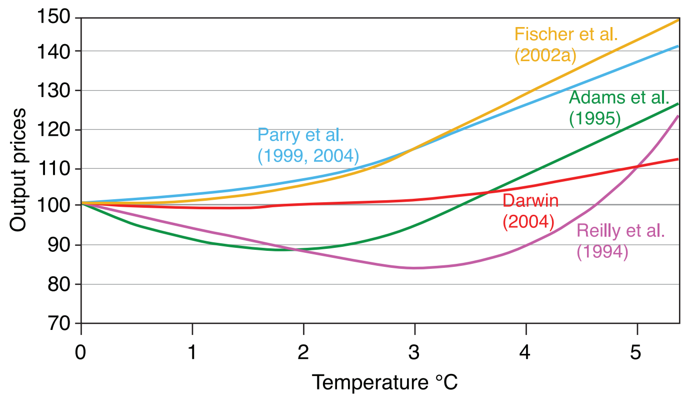

Figure 5.3. *Cereal prices (percent of baseline) versus global mean temperature change for major modelling studies. Prices interpolated from point estimates of temperature effects.*

5.6.2 Global costs to forestry

Alig et al. (2004) suggest that climate variability and climate change may alter the productivity of forests and thereby shift 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 modify the prices of forest products, impact economic welfare and affect land-use changes. Current studies consider mainly the impact of climate change on forest resources, industry and economy; however, some analyses include feedbacks in the ecological system, including greenhouse gas cycling in forest ecosystems and forest products (e.g., Sohngen and Sedjo, 2005). A number of studies analyse the effects of climate change on the forest industry and economy (e.g., Binkley, 1988; Joyce et al., 1995; Perez-Garcia et al., 1997; Sohngen and Mendelsohn, 1998; Shugart et al., 2003; see Table 5.4 and Section 5.4.5).

If the world develops as the models predict, there will be a general decline of wood raw-material prices due to increased wood production (Perez-Garcia et al., 1997; Sohngen and Mendelsohn, 1998). The same authors conclude that economic welfare effects are relatively small but positive, with net benefits accruing to wood consumers. However, changes in other sectors, such as major shifts in demand and requirements for energy production, will also impact prices in the forest sector. There are no concrete studies on non-wood services from forest resources, but the impacts of climate change on many of these services will likely be spatially specific.

5.6.3 Changes in trade

The principal impact of climate change on agriculture is an increase in production potential in mid- to high-latitudes and a decrease in low latitudes. This shift in production potential is expected to result in higher trade flows of mid- to high-latitude products (e.g., cereals and livestock products) to the low latitudes. Fischer et al. (2002b) estimate that by 2080 cereal imports by developing countries would rise by 10-40%.

5.6.4 Regional costs and associated socio-economic impacts

Fischer et al. (2002b) quantified regional impacts and concluded that globally there will be major gains in potential agricultural land by 2080, particularly in North America (20-50%) and the Russian Federation (40-70%), but losses of up to 9% in sub-Saharan Africa. The regions likely to face the biggest challenges in food security are Africa, particularly sub-Saharan Africa, and Asia, particularly south Asia (FAO, 2006).

Africa

Yields of grains and other crops could decrease substantially across the African continent because of increased frequency of drought, even if potential production increases due to increases in CO_2 concentrations. Some crops (e.g., maize) could be discontinued in some areas. Livestock production would suffer due to deteriorated rangeland quality and changes in area from rangeland to unproductive shrub land and desert.

Asia

According to Murdiyarso (2000), rice production in Asia could decline by 3.8% during the current century. Similarly, a 2°C increase in mean air temperature could decrease rice yield by about 0.75 tonne/ha in India and rain-fed rice yield in China by 5-12% (Lin et al., 2005). Areas suitable for growing wheat could decrease in large portions of south Asia and the southern part of east Asia (Fischer et al., 2002b). For example, without the CO_2 fertilisation effect, a 0.5°C increase in winter temperature would reduce wheat yield by 0.45 ton/ha in India (Kalra et al., 2003) and rain-fed wheat yield by 4-7% in China by 2050. However, wheat production in both countries would increase by between 7% and 25% in 2050 if the CO_2 fertilisation effect is taken into account (Lin et al., 2005).

5.6.5 Food security and vulnerability

All four dimensions of food security, namely food availability (i.e., production and trade), stability of food supplies, access to food, and food utilisation (FAO, 2003a) will likely be affected by climate change. Importantly, food security will depend not only on climate and socio-economic impacts, but also, and critically so, on changes to trade flows, stocks and food-aid policy. Climate change impacts on food production (*food availability*) will be mixed and vary regionally (FAO, 2003b, 2005c). For instance, a reduction in the production potential of tropical developing countries, many of which have poor land and water resources, and are already faced with serious food insecurity, may add to the burden of these countries (e.g., Hitz and Smith, 2004; Fischer et al., 2005a; Parry et al., 2005). Globally, the potential for food production is projected to increase with increases in local average temperature over a range of 1 to 3°C, but above this it is projected to decrease. Changes in the patterns of extreme events, such as increased frequency and intensity of droughts and flooding, will affect the *stability* of, as well as *access* to, food supplies. 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 (FAO, 2003c).

Climate change may also affect food *utilisation*, notably through additional health consequences (see Chapter 8). For example, populations in water-scarce regions are likely to face decreased water availability, particularly in the sub-tropics, with implications for food processing and consumption; in coastal areas, the risk of flooding of human settlements may increase, from both sea level rise and increased heavy precipitation. This is likely to result in an increase in the number of people exposed to vector-borne (e.g., malaria) and water-borne (e.g., cholera) diseases, thus lowering their capacity to utilise food effectively.

A number of studies have quantified the impacts of climate change on food security at regional and global scales (e.g., Fischer et al., 2002b, 2005b; Parry et al., 2004, 2005; Tubiello and Fischer, 2006). These projections are based on complex modelling frameworks that integrate the outputs of GCMs, agro-ecological zone data and/or dynamic crop models, and socio-economic models. In these systems, impacts of climate change on agronomic production potentials are first computed; then consequences for food supply, demand and consumption at regional to global levels are computed, taking into account different socio-economic futures (typically SRES scenarios). A number of limitations, however, make these model projections highly uncertain. First, these estimates are limited to the impacts of climate change mainly on food availability; they do not cover potential changes in the stability of food supplies, for instance, in the face of changes to climate and/or socio-economic variability. Second, projections are based on a limited number of crop models, and only one economic model (see legend in Table 5.6), the latter lacking sufficient evaluation against observations, and thus in need of further improvements.

Despite these limitations and uncertainties, a number of fairly robust findings for policy use emerge from these studies. *First*, climate change is likely to increase the number of people at risk of hunger compared with reference scenarios with no climate change. However, impacts will depend strongly on projected socio-economic developments (Table 5.6). For instance, Fischer et al. (2002a, 2005b) estimate that climate change will increase the number of undernourished people in 2080 by 5-26%, relative to the no climate change case, or by between 5-10 million (SRES B1) and 120-170 million people (SRES A2). The within-SRES ranges are across several GCM climate projections. Using only one GCM scenario, Parry et al. (2004, 2005) estimated small reductions by 2080, i.e., –5% (–10 [B] to –30 [A2] million people), and slight increases of +13-26% (10 [B2] to 30 [A1] million people).

Second, the magnitude of these climate impacts will be small compared with the impacts of socio-economic development (e.g., Tubiello et al., 2007b). With reference to Table 5.6, these studies suggest that economic growth and slowing population growth projected for the 21st century will, globally, significantly reduce the number of people at risk of hunger in 2080 from current levels. Specifically, compared with FAO estimates of 820 million undernourished in developing countries today, Fischer et al. (2002a, 2005b) and Parry et al. (2004, 2005) estimate reductions by more than 75% by 2080, or by about 560-700 million people, thus projecting a global total of 100-240 million undernourished by 2080 (A1, B1 and B2). By contrast, in A2, the number of the hungry may decrease only slightly in 2080, because of larger population projections compared with other SRES scenarios (Fischer et al., 2002a, 2005b; Parry et al., 2004, 2005; Tubiello and Fischer, 2006). These projections also indicate that, with or without climate change, Millennium Development Goals (MDGs) of halving the proportion of people at risk of hunger by 2015 may not be realised until 2020-2030 (Fischer et al., 2005b; Tubiello, 2005).

Third, sub-Saharan Africa is likely to surpass Asia as the most food-insecure region. However, this is largely independent of climate change and is mostly the result of the projected socio-economic developments for the different developing regions. Studies using various SRES scenarios and model analyses indicate that by 2080 sub-Saharan Africa may account for 40-50% of all undernourished people, compared with about 24% today (Fischer et al., 2002a, 2005b; Parry et al., 2004, 2005); some estimates are as high as 70-75% under the A2 and B2 assumptions of slower economic growth (Fischer et al., 2002a; Parry et al., 2004; Tubiello and Fischer, 2006).

Fourth, there is significant uncertainty concerning the effects of elevated CO_2 on food security. With reference to Table 5.6, under most future scenarios the assumed strength of CO_2 fertilisation would not greatly affect global projections of hunger, particularly when compared with the absolute reductions attributed solely to socio-economic development (Tubiello et al., 2007a,b). For instance, employing one GCM, but assuming no effects of CO_2 on crops, Fischer et al. (2002a, 2005b) and Parry et al. (2004, 2005) projected absolute global numbers of undernourished in 2080 in the range of 120-380 million people across SRES scenarios A1, B1 and B2, as opposed to a range of 100-240 million when account is taken of CO_2 effects. The exception again in these studies is SRES A2, under which scenario the assumption of no CO_2 fertilisation results in a projected range of 950-1,300 million people undernourished in 2080, compared with 740-850 million with climate change and CO_2 effects on crops.

Finally, recent research suggests large positive effects of climate mitigation on the agricultural sector, although benefits, in terms of avoided impacts, may be realised only in the second half of this century due to the inertia of global mean temperature and the easing of positive effects of elevated CO_2 in the mitigated scenarios (Arnell et al., 2002; Tubiello and Fischer, 2006). Even in the presence of robust global long-term benefits, regional and temporal patterns of winners and losers are highly uncertain and critically dependent on GCM projections (Tubiello and Fischer, 2006).

Table 5.6. *The impacts of climate change and socio-economic development paths on the number of people at risk of hunger in developing countries (data from Parry et al., 2004; Tubiello et al., 2007b). The first set of rows in the table depicts reference projections under SRES scenarios and no climate change. The second set (CC) includes climate change impacts, based on Hadley HadCM3 model output, including positive effects of elevated CO_2 on crops. The third (CC, no CO_2) includes climate change, but assumes no effects of elevated CO_2. Projections from 2020 to 2080 are given for two crop-modelling systems: on the left, AEZ (Fischer et al., 2005b); on the right, DSSAT (Parry et al., 2004), each coupled to the same economic and food trade model, BLS (Fischer et al., 2002a, 2005b). The models are calibrated to give 824 million undernourished in 2000, according to FAO data.*

	2020		2050		2080	
	Millions at risk		Millions at risk		Millions at risk	
Reference	**AEZ-BLS**	**DSSAT-BLS**	**AEZ-BLS**	**DSSAT-BLS**	**AEZ-BLS**	**DSSAT-BLS**
A1	663	663	208	208	108	108
A2	782	782	721	721	768	769
B1	749	749	239	240	91	90
B2	630	630	348	348	233	233
CC	**AEZ-BLS**	**DSSAT-BLS**	**AEZ-BLS**	**DSSAT-BLS**	**AEZ-BLS**	**DSSAT-BLS**
A1	666	687	219	210	136	136
A2	777	805	730	722	885	742
B1	739	771	242	242	99	102
B2	640	660	336	358	244	221
CC, no CO_2	**AEZ-BLS**	**DSSAT-BLS**	**AEZ-BLS**	**DSSAT-BLS**	**AEZ-BLS**	**DSSAT-BLS**
A1	NA	726	NA	308	NA	370
A2	794	845	788	933	950	1320
B1	NA	792	NA	275	NA	125
B2	652	685	356	415	257	384

5.7 Implications for sustainable development

Human societies have, through the centuries, often developed the capacity to adapt to environmental change, and some knowledge about the implications of climate change adaptation for sustainable development can thus be deduced from historical analogues (Diamond, 2004; Easterling et al., 2004).

Unilateral adaptation measures to water shortage related to climate change can lead to competition for water resources and, potentially, to conflict and backlash for development. International and regional approaches are required to develop joint solutions, such as the three-border project Trifinio in Lempa valley between Honduras, Guatemala and El Salvador (Dalby, 2004). Shifts in land productivity may lead to a shift in agriculture and livestock systems in some regions, and to agricultural intensification in others. This results not only in environmental benefits, such as less habitat loss and lower carbon emissions (Goklany, 1998, 2005), but also in environmental costs, such as soil degradation, siltation, reduced biodiversity and others (Stoate et al., 2001).

Adaptive measures in response to habitat and ecosystem shifts, such as expansion of agriculture into previously forested areas, will lead to additional loss and fragmentation of habitats. Currently, deforestation, mainly a result of conversion of forests to agricultural land, continues at a rate of 13 million ha/yr (FAO, 2005b). The degradation of ecosystem services not only poses a barrier to achieving sustainable development in general, but also to meeting specific international development goals, notably the MDGs (Millennium Ecosystem Assessment, 2005). The largest forest losses have occurred in South America and Africa, often in countries marked by high reliance on solid fuels, low levels of access to safe water and sanitation, and the slowest progress towards the MDG targets. Response strategies aimed at minimising such losses will have to focus increasingly on regional and international landscape development (Opdam and Wascher, 2004).

Impacts on trade, economic development and environmental quality, as well as land use, may also be expected from measures to substitute fossil fuels with biofuels, such as the European Biomass Action Plan. It may be necessary to balance competition between the energy and forest products sectors for raw materials, and competition for land for biofuels, food and forestry.

Sustainable economic development and poverty reduction remain top priorities for developing countries (Aggarwal et al., 2004). Climate change could exacerbate climate-sensitive hurdles to sustainable development faced by developing countries (Goklany, 2007). This will require integrated approaches to concurrently advance adaptation, mitigation and sustainable development. Goklany (2007) also offers a portfolio of pro-active strategies and measures, including measures that would simultaneously reduce pressures on biodiversity, hunger and carbon sinks. Moreover, any adaptation measures should be developed as part of, and be closely integrated into, overall and country-specific development programmes and strategies, e.g., into Poverty Reduction Strategy Programmes (Eriksen and Naess, 2003) and pro-poor strategies (Kurukulasuriya and Rosenthal, 2003), and should be understood as a 'shared responsibility' (Ravindranath and Sathaye, 2002).

5.8 Key conclusions and their uncertainties, confidence levels and research gaps

5.8.1 Findings and key conclusions

Projected changes in the frequency and severity of extreme climate events will have more serious consequences for food and forestry production, and food insecurity, than will changes in projected means of temperature and precipitation (high confidence).

Modelling studies suggest that increasing frequency of crop loss due to extreme events, such as droughts and heavy precipitation, may overcome positive effects of moderate temperature increase [5.4.1]. For forests, elevated risks of fires, insect outbreaks, wind damage and other forest-disturbance events are projected, although little is known about their overall effect on timber production [5.4.1].

Climate change increases the number of people at risk of hunger (high confidence). The impact of chosen socio-economic pathways (SRES scenario) on the numbers of people at risk of hunger is significantly greater than the impact of climate change. Climate change will further shift the focus of food insecurity to sub-Saharan Africa.

Climate change alone is estimated to increase the number of undernourished people to between 40 million and 170 million. By contrast, the impacts of socio-economic development paths (SRES) can amount to several hundred million people at risk of hunger [5.6.5]. Moreover, climate change is likely to further shift the regional focus of food insecurity to sub-Saharan Africa. By 2080, about 75% of all people at risk of hunger are estimated to live in this region. The effects of climate mitigation measures are likely to remain relatively small in the early decades; significant benefits of mitigation to the agricultural sector may be realised only in the second half of this century, i.e., once the positive CO_2 effects on crop yields level off and global mean temperature increases become significantly less than in non-mitigated scenarios [5.6.5].

While moderate warming benefits crop and pasture yields in mid- to high-latitude regions, even slight warming decreases yields in seasonally dry and low-latitude 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 rain-fed crops (maize, wheat, rice) and pastures in mid- to high-latitude 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 and see Figure 5.2]. These results, on the whole, project the potential for global food production to increase with increases in local average temperature over a range of 1 to 3ºC, but above this range to decrease [5.4, 5.6]. 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].

Experimental research on crop response to elevated CO_2 confirms Third Assessment Report (TAR) findings (medium to high confidence). New Free-Air Carbon Dioxide Enrichment (FACE) results suggest lower responses for forests (medium confidence). 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 FACE studies of CO_2 fertilisation confirm conclusions from the TAR that crop yields at CO_2 levels of 550 ppm increase by an average of 15%. Crop model estimates of CO_2 fertilisation are in the range of FACE results [5.4.1.1]. For forests, FACE experiments suggest an average growth increase of 23% for younger tree stands, but little stem-growth enhancement for mature trees. The models often assume higher growth stimulation than FACE, up to 35% [5.4.1.1, 5.4.5].

Globally, commercial timber productivity rises modestly with climate change in the short and medium term, with large regional variability around the global trend (medium 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 CO_2 fertilisation and the effect of disturbance processes not well represented in the models (e.g., insect outbreaks), although regional and local changes will be large [5.4.5.2].

Local extinctions of particular fish species are expected at edges of ranges (high confidence).

Regional changes in the distribution and productivity of particular fish species are expected because of continued warming 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 the 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 dependence of most developing countries on food imports (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 is already challenged in many of the regions expected to suffer more severe yield declines. Agricultural and forestry trade flows are foreseen to rise significantly. Exports of food products from the mid and high latitudes to low latitude 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 food, fibre, forestry and fishery (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 benefits of adaptation tend 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 [5.9].

Summary of Impacts and Adaptive Results by Temperature and Time. Major generalisations across the FFFF sectors distilled from the literature are reported either by increments of temperature increase (Table 5.7) or by increments of time (Table 5.8), depending on how the information is originally reported. A global map of regional impacts of FFFF is shown in Figure 5.4.

5.8.2 Research gaps and priorities

Key knowledge gaps that hinder assessments of climate change consequences for FFFF and their accompanying research priorities are listed in Table 5.9.

Table 5.7. *Summary of selected conclusions for food, fibre, forestry, and fisheries, by warming increments.*

Temp. Change	Sub-sector	Region	Finding	Source section
+1 to +2°C	Food crops	Mid- to high-latitudes	- Cold limitation alleviated for all crops - Adaptation of maize and wheat increases yield 10-15%; rice yield no change; regional variation is high	Figure 5.2
	Pastures and livestock	Temperate	- Cold limitation alleviated for pastures; seasonal increased frequency of heat stress for livestock	Table 5.3
	Food crops	Low latitudes	- Wheat and maize yields reduced below baseline levels; rice is unchanged - Adaptation of maize, wheat, rice maintains yields at current levels	Figure 5.2
	Pastures and livestock	Semi-arid	- No increase in NPP; seasonal increased frequency of heat stress for livestock	Table 5.3
	Prices	Global	- Agricultural prices: –10 to –30%	Figure 5.3
+2 to +3°C	Food crops	Global	- 550 ppm CO_2 (approx. equal to +2°C) increases C_3 crop yield by 17%; this increase is offset by temperature increase of 2°C assuming no adaptation and 3°C with adaptation	Figure 5.2
	Prices	Global	- Agricultural prices: –10 to +20%	Figure 5.3
	Food crops	Mid- to high-latitudes	- Adaptation increases all crops above baseline yield	Figure 5.2
	Fisheries	Temperate	- Positive effect on trout in winter, negative in summer	5.4.6.1
	Pastures and livestock	Temperate	- Moderate production loss in swine and confined cattle	Table 5.3
	Fibre	Temperate	- Yields decrease by 9%	5.4.4
	Pastures and livestock	Semi-arid	- Reduction in animal weight and pasture production, and increased heat stress for livestock	Table 5.3
	Food crops	Low latitudes	- Adaptation maintains yields of all crops above baseline; yields drops below baseline for all crops without adaptation	Figure 5.2
+3 to +5°C	Prices and trade	Global	- Reversal of downward trend in wood prices - Agricultural prices: +10 to +40% - Cereal imports of developing countries to increase by 10-40%	5.4.5.1 Figure 5.3 5.6.3
	Forestry	Temperate	- Increase in fire hazard and insect damage	5.4.5.3
		Tropical	- Massive Amazonian deforestation possible	5.4.5
	Food crops	Low latitudes	- Adaptation maintains yields of all crops above baseline; yield drops below baseline for all crops without adaptation	Figure 5.2
	Pastures and livestock	Tropical	- Strong production loss in swine and confined cattle	Table 5.3
	Food crops	Low latitudes	- Maize and wheat yields reduced below baseline regardless of adaptation, but adaptation maintains rice yield at baseline levels	Figure 5.2
	Pastures and livestock	Semi-arid	- Reduction in animal weight and pasture growth; increased animal heat stress and mortality	Table 5.3

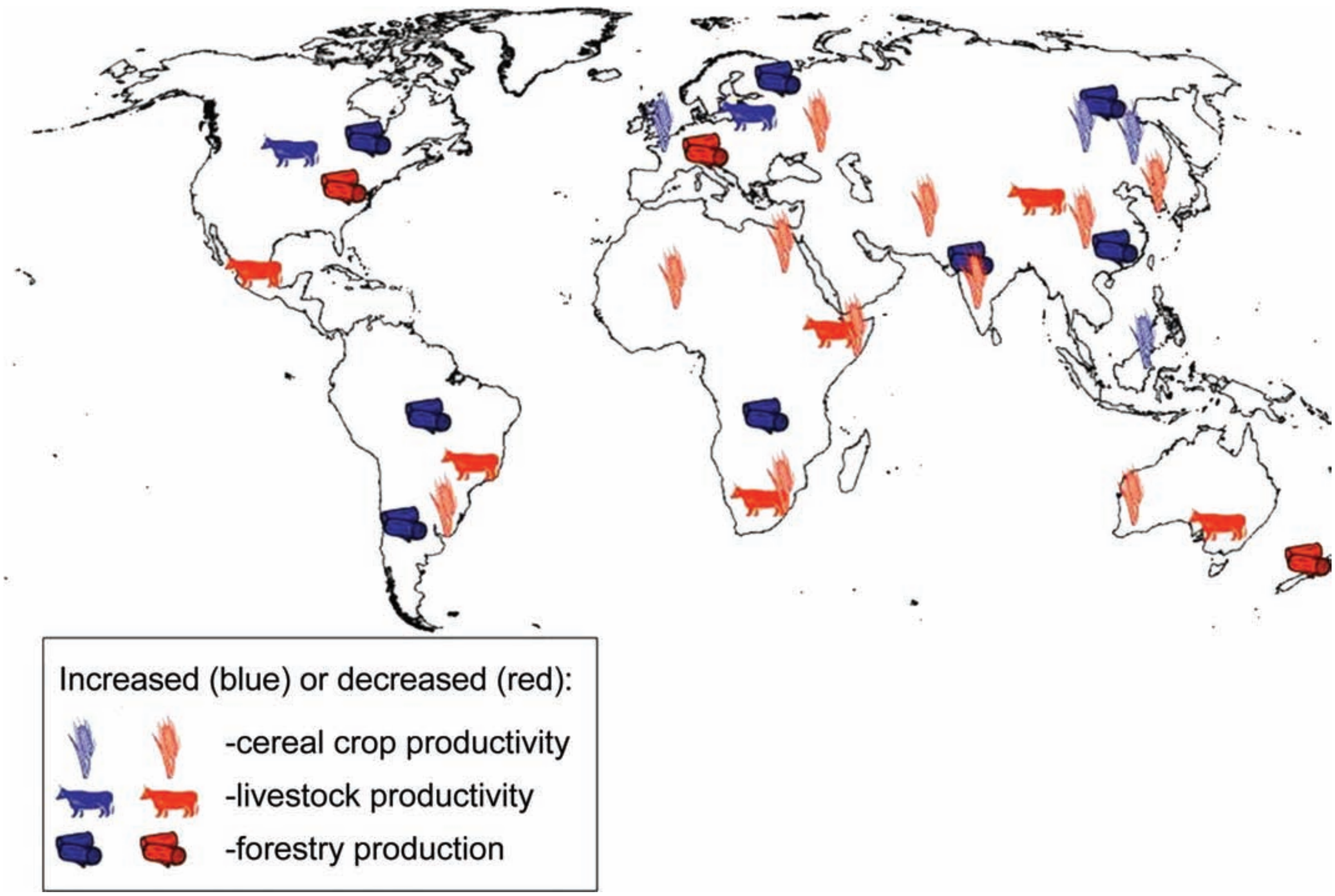

Figure 5.4. *Major impacts of climate change on crop and livestock yields, and forestry production by 2050 based on literature and expert judgement of Chapter 5 Lead Authors. Adaptation is not taken into account.*

Table 5.8. *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, e.g., increased heavy precipitation, cause crop losses to US$3 billion by 2030 with respect to current levels	5.4.2
	Small-holder farming, fishing	Low latitudes, especially east and south Africa	- Decline in maize yields, increased risk of crop failure, high livestock mortality	5.4.7
	Small-holder farming, fishing	Low latitudes, especially south Asia	- Early snow melt causing spring flooding and summer irrigation shortage	5.4.7
	Forestry	Global	- Increased export of timber from temperate to tropical countries - Increase in share of timber production from plantations - Timber production +5 to +15%	5.4.5.2 Table 5.4
2050	Fisheries	Global	- Marine primary production +0.7 to +8.1%, with large regional variation (see Chapter 4)	5.4.6.2
	Food crops	Global	- With adaptation, yields of wheat, rice, maize above baseline levels in mid- to high-latitude regions and at baseline levels in low latitudes.	Figure 5.2
	Forestry	Global	- Timber production +20 to +40%	Table 5.4
2080	Food crops	Global	- Crop irrigation water requirement increases 5-20%, with range due to significant regional variation	5.4.2
	Forestry	Global	- Timber production +20 to +60% with high regional variation	Table 5.4
	Agriculture sector	Global	- Stabilisation at 550 ppm ameliorates 70-100% of agricultural cost caused by unabated climate change	5.4.2

Table 5.9. *Key knowledge gaps and research priorities for food, fibre, forestry, and fisheries (FFFF).*

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 and 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 the 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 and technological components within integrated assessment models are needed, including new global simulation studies that incorporate new crop, forestry and livestock knowledge in models.
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 prioritisation, adaptation research has failed to provide generalised knowledge of the adaptive capacity of FFFF systems across a range of climate and socio-economic futures, and across developed and developing countries (including commercial and small-holder operations).	A more complete 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 time-lags 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 Fourth Assessment assume 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 and critique the SRES scenarios.
Relatively moderate impacts of climate change on 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.
The impact of climate change on utilisation of biofuel crops is not well established.	Research on biomass feed stock crops such as switchgrass and short-rotation poplar is needed. Research is needed on the competition for land between bio-energy crops and food crops.

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