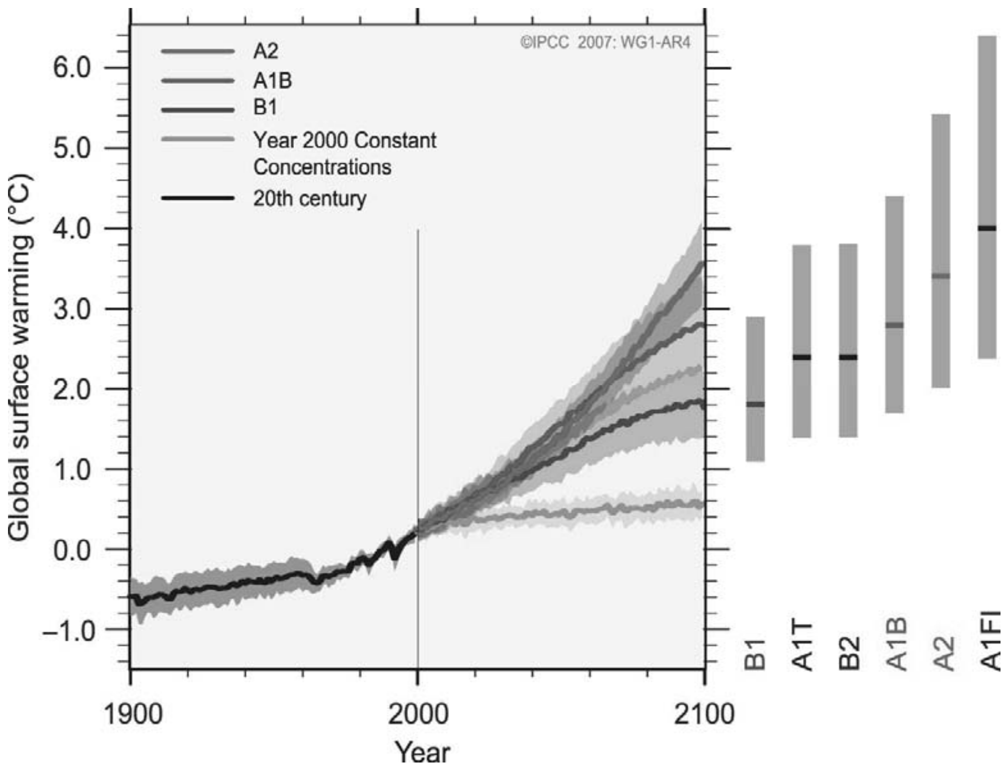
Chapter 2
Climate change projections

IPCC projections

The impacts of climate change are likely to be greater on those countries more dependent on primary sector economic activities, primarily because of the increase in uncertainty on productivity on these primary sectors. Impacts include reduction in water availability in already water-stressed areas, changes in the incidence of extreme events such as typhoons and droughts, and impacts of sea level rise in low-lying coastal areas (see Easterling *et al.* [2007] for a summary). Modern agriculture has tried to minimise the impacts of climatic and weather uncertainty through irrigation, the substitution of labour with energy-intensive practices and plant breeding for heat or water-stress tolerant crops. Thus adaptation in agriculture takes places either by farmers individually, by farmers and local institutions collectively, or through national level policy decisions which provide finance, research and development, and knowledge transfer, and property rights or legal frameworks to enable individual or collective action.

The impacts of climate change on agriculture come about through changes in variability, seasonality, changes in mean precipitation and water availability, and the emergence of new pathogens and diseases (Fischlin *et al.,* 2007). Each of these mechanisms is likely to become more significant with higher rising temperatures, and clearly the overall impacts of climate change in agriculture depends on the interactions between these mechanisms – where new pests, water availability and thresholds in temperature interact, for example. Figure 2.1 shows the range of projections of climate change to 2100 from the *Fourth Assessment Report* (AR4) of the IPCC (IPCC, 2007a). The range of projections (1.4-5.8°C by 2100) comes about both because of uncertainty in the physical models of climate forcing and response, and also from uncertainty about future emissions that are dependent on technological change, human population growth and other factors (O'Neill *et al.,* 2001). Much evidence within the IPCC Working Group report on impacts adaptation and vulnerability (IPCC, 2007b), suggests that there are impacts related to these projected temperature increases. These include impacts on water stress, on extreme events and on pathogens and diseases that also become more likely and more significant with the projected rising temperatures. In other words, the projected temperature increases for the incoming century in Figure 2.1 will be correlated with rising dangerous impacts of climate change on ecosystems, widespread aggregate impacts, and risk of catastrophic irreversible impacts (Mastandrea and Schneider, 2004; Schneider, 2004).

Figure 2.1. IPCC *Fourth Assessment Report* projections of global mean temperature for six representative emissions scenarios and a range of climate sensitivities



Source: IPCC (2007a).

Some impacts of climate change are already apparent in recent extreme events throughout the world. Drought, floods and heatwaves became more common in the 20th century, while the 1990s were the warmest decade in the so-called "instrumental" record of observed temperature around the world (Jones and Moberg, 2003). The warmest year of the entire series was 1998, with a temperature of 0.58°C above the 1961-90 mean. Nine of the ten warmest years in the series have now occurred in the past ten years (1995-2004). Observed impacts of climate change on physical and ecological systems over the past century (documented in IPCC [2007a] and Parmesan and Yohe, 2003, for example) are forerunners of things to come. Along with changes in mean climatic conditions, the earth potentially faces irreversible and catastrophic system feedbacks and impacts associated, for example, with collapse of thermohaline circulation, the melting of the Greenland ice sheet (Gregory *et al.,* 2004), or other singular events (Alley *et al.,* 2003). Societies, organisations and individuals have adjusted their behaviour in response to past climatic changes, and many are now contemplating adapting to altered future climatic conditions. Much of this adaptation is reactive, in the sense that it is triggered by past or current events, but it is also anticipatory, in the sense that it is based on some assessment of conditions in the future (Smit *et al.,* 2000).

In the IPCC *Fourth Assessment Report* projections of global mean temperature for six representative emissions scenarios and a range of climate sensitivities, the bars show, for each of the six main scenarios used by the IPCC (of 35 possible futures), the range of the model results in 2100. The grey bars at the right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints (IPCC, 2007a).

Agronomic research indicates that higher temperatures associated with climatic change will be harmful to the production of many crop and livestock groups. Where there is water stress, heat stress or a combination of the two, the world's cereal crops can be vulnerable to even minor changes in temperature. The agronomy of all crops will be affected by both temperature and precipitation change and by the increased atmospheric concentration of carbon dioxide. Rice, for example, is predicted to experience increased yield due to CO_2 fertilization at higher concentrations than present (around 380 ppmv). But it is estimated that the net yield increase turns negative as temperature increases by 3 or 4°C. However, these crop model projections often hold precipitation constant and it is seasonal water availability, which most heavily influences crop yield changes, that may, for example, affect the largest grain-growing areas of the Asian sub-continent (see Lal *et al.,* 1998 and Matthews *et al.,* 1997). The feedback impacts of climate change on production of the major crops such as rice and wheat are therefore highly uncertain (see discussion below). The IPCC reports from 1996, 2001 and 2007 (Reilly *et al.,* 1996; Gitay *et al.,* 2001; Easterling *et al.,* 2007) review the results of available studies and conclude that the overall direction suggests negative impacts on crop productivity and yields for the tropics, while there is contested evidence for beneficial effects for the high latitudes. At +2 to +3 degrees agricultural prices are expected to be affected, however the impact ranges from -10 to +20%, depending on the model used, however at +3 to +5 degrees agricultural prices are expected to increase by between 10 and 40%, while cereal imports of developing countries are likely to increase by 10-40% (Easterling *et al.,* 2007). The main findings are summarised in Table 2.1. The main projected impacts are discussed in further detail in the following chapter.

Primary effects and interactions

The food and fibre chapter in the most recent IPCC report, the AR4 (Easterling *et al.,* 2007) provides a comprehensive update of findings since the Third Assessment Report.

Effects of elevated CO_2: Studies at plot level over the last few decades have indicated that plant biomass and yield increase significantly at higher than present CO_2 levels. There are two responses involved; the photosynthetic response which leads to increased plant productivity, and the crop yield response. The crop yield response is lower than the photosynthetic response, however it could potentially lead to increases in yield of up to 20% (Nowak *et al.,* 2004; Ainsworth and Long 2005; Long *et al.,* 2004). The effects of elevated CO_2 on plant growth and yield however will depend on photosynthetic pathway, species, growth stage and management regime (Jablonski *et al.,* 2008; Kimball *et al.,* 2002; Norby *et al.,* 2003). It was recently suggested (Long *et al.,* 2005; 2006) that crop responses to elevated CO_2 were not as high as previously thought, however the latest research (Tubiello *et al.,* 2006) has confirmed the original findings with new results. Suggestions that current impact assessment simulation results are too optimistic in their assumptions about CO_2 response are now shown to be incorrect (Tubiello *et al.,* 2007).

While the effect of CO_2 may show positive effects on plant growth in experiments, the results of plot level experiments are likely to overestimate the reality of the CO_2 response because of complicating factors which occur in the real world and not in the experiments, such as pests and weeds, lack of and competition for other necessary resources, and extreme events. These interactions are not well understood at large scales nor well implemented in leading models (Easterling *et al.,* 2007).

Table 2.1. Summary of selected conclusions from IPCC for food and fibre

Temperature change	Sub-sector	Region	Finding
+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
	Pastures and livestock	Temperate	• Cold limitation alleviated for pastures; seasonal increased frequency of heat stress for livestock
	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
	Pastures and livestock	Semi-arid	• No increase in NPP; seasonal increased frequency of heat stress for livestock • Agricultural prices: -10 to -30%
+2 to +3°C	Food crops	Global	• 550 ppm CO_2 increases C3 crop yield by 17%; this is offset by temperature increase of 2°C assuming no adaptation and 3°C with adaptation
	Food crops	Mid- to high latitudes	• Adaptation increases all crops above baseline yield
	Pastures and livestock	Temperate	• Moderate production loss in swine and confined cattle

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(Table 2.1 continued)

Temperature change	Sub-sector	Region	Finding
	Fibre	Temperate	• Yields decrease by 9%
	Pastures and livestock	Semi-arid	• Reduction in animal weight and pasture production, and increased heat stress for livestock
	Food crops	Low latitudes	• Adaptation maintains yields of all crops above baseline; yields drop below baseline for all crops without adaptation
+3 to +5°C	Food crops	Low latitudes	• Adaptation maintains yields of all crops above baseline; yield drops below baseline for all crops without adaptation
	Pastures and livestock	Tropical	• Strong production loss in swine and confined cattle
	Food crops	Low latitudes	• Maize and wheat yields reduced below baseline regardless of adaptation, but adaptation maintains rice yield at baseline levels
	Pastures and livestock	Semi-arid	• Reduction in animal weight and pasture growth; increased animal heat stress and mortality

Source: Adapted from Easterling *et al.,* 2007.

Interactions of elevated CO_2 with other factors: Although an increase in CO_2 in isolation from other factors is shown to increase crop growth and productivity, these effects will often be countered in reality by other changes in the system. Higher temperatures during certain growth stages may be detrimental to yield and quality (Caldwell *et al.,* 2005; Baker, 2004; Thomas *et al.,* 2003). Increased growth caused by elevated CO_2 may lead to greater water demand (Xiao *et al.,* 2005), which in many parts of the world may be combined with increasing pressure on water resources, which may also be declining, and hence become a limiting factor. Climate impacts on crops may depend heavily on the precipitation scenario considered. Similarly, the availability of soil nutrients such as nitrogen and phosphorus may also prove to be limiting factors in the CO_2 response. Studies have shown that high soil N contents increase the relative response to elevated CO_2 concentrations (Nowak *et al.,* 2004).

Increased frequency of extreme events: The increased frequency and intensity of extreme events, such as floods, droughts, heat waves, and windstorms is likely to lead to greater production losses than any increase in mean temperature (Porter and Semenov 2005). Both short duration events such as heatwaves and floods, as well as longer-term events with sustained above normal temperatures have the potential to cause considerable damage to crops and yields depending on their occurrence in the growing season. Large-scale circulation changes such as the El-Niño Southern Oscillation (ENSO) have important impacts on production and therefore GDP. In Australia the effect of the drought in 2002-03 caused a reduction in GDP of 1.6% (O'Meagher 2005). The 2003 heatwave in Europe, which broke several temperature records, resulted in a fall in corn yield in Italy of 36% (Cias *et al.,* 2005), and is likely to be indicative of future summers (Schaer *et al.,* 2004). Understanding the links between increased frequency of extreme events and ecosystem disturbances is very important, however few models consider effects of climate variability as well as mean variables.

Impacts on weeds, pests, diseases and animal health: Although the qualitative picture of interactions between CO_2 and pests, diseases and weeds is understood, quantitative information is currently still lacking. Interactions between CO_2 and temperature are recognised as a key determinant in plant damage from pests in the future, and interactions between CO_2 and precipitation are also likely to be important (Zvera and Kozlov, 2006; Stacey and Fellows, 2002). However, most studies continue to investigate pest damage in response to either CO_2 (Agrell *et al.,* 2004; Chakraborty and Datta 2003; Chen *et al.,* 2005) or temperature, but not in combination.

Increased climate extremes may promote plant disease and pest outbreaks. Studies have shown that the spread of animal diseases from low to mid-latitudes is occurring already. Bluetongue, a disease affecting sheep and cattle, and is already spreading from the tropics to the mid-latitudes including France, the United Kingdom and Nordic countries, while cattle tick *(Boophilus microplus)* may affect the Australian beef industry.

Rosenzweig *et al.* (2000, 2001) review the major threats to agriculture associated with diseases and pests as well as drought and floods with global evidence and examples from the US. They highlight the 1988 drought in the US Midwest that cost USD 3 billion in compensation and subsidies. The Mississippi floods of summer 1993 affected 16 000 square miles of farmland with 11 million acres of crops damaged, with an estimated cost of USD 23 billion, as well as emergency measures to drain land in Iowa alone costing USD 222 million. In terms of pathogens, these floods contributed to the so-called "Dead Zone" of algal bloom in the Gulf of Mexico through nutrients and other chemicals runoff into the Mississippi (Rosenzweig *et al.,* 2001). The ranges of particular pests in the United States, including the soybean cyst nematode and corn grey leaf blight, have expanded since the 1970s due to increasingly favourable climatic conditions. Projections of climate change globally show that higher temperatures and greater precipitation (in some regions) are likely to result in the spread of novel pathogens and diseases. Shorter winters lead to less insect kill and wet vegetation promotes proliferation of bacteria, while prolonged dry periods (in other regions) encourage insect-promoted diseases. Such indirect impacts of climate change on agriculture are potentially important but a largely unknown impact.

Sudden changes in climate, such as severe weather events, often result in large losses to stock in confined cattle lots, as they have no prior conditioning to these events (Mader, 2003). High temperatures and droughts are likely to induce increases in mortality, yields and conception rates, for animals not accustomed to the higher temperatures (IPCC, 2007).

Interaction with air pollutants: Tropospheric ozone has been shown to have significant adverse effects on crop yields, pasture and forest growth, and species composition (IPCC, 2007). Direct and indirect interactions between global ozone and elevated CO_2 is likely to further modify plant dynamics (Fiscus *et al.,* 2005; Booker *et al.,* 2005). Although it has been shown that elevated CO_2 may minimise negative impacts from ozone, the interactions between the two have not been considered sufficiently in current risk assessments.

Vulnerability of carbon pools: Climate change has the potential to affect the global terrestrial carbon sink and to further perturb atmospheric CO_2 concentrations (Cias *et al.,* 2005; Betts *et al.,* 2004). Land-use planning and management practices, including set-aside policies, reforestation, and N fertilization, irrigation and tillage practices all have the potential to affect future changes in carbon stocks and fluxes. Carbon stored in soil organic matter has been shown to be affected by atmospheric CO_2 levels (Allard *et al.,* 2005; Gill *et al.,* 2002), temperature (Ciais *et al.,* 2005), and air pollution (Loya *et al.,* 2003; Booker *et al.,* 2005), although considerable uncertainty remains. These relationships highlight the importance of co-ordinating adaptation and mitigation strategies and considering the effects of climate policy on land-use change and long-term sustainability of production systems (Rosenzweig *et al.,* 2007).

Impact assessments: Results from integrated assessment and crop models over the 20 years indicate consistently that impacts in the agricultural sector are likely to be small in the first half of the 21st century – although they are likely to become increasingly negative in the second half, as mean temperatures increase (IPCC, 2007; 2001). However, uncertainties which could potentially alter these findings consist of a range of factors, from the strength and saturation point of the elevated CO_2 response of crops grown in real fields rather than experimental plots, to the timing and implementation of adaptation strategies and the interaction between mitigation and adaptation strategies (Tubiello *et al.,* 2007).

Food crop farming: The possibility for surprise events that are not considered in impact assessments cannot be ruled out. The most recent IPCC report lists three main factors which have not been considered in modelling to date:

- Increases in the frequency of climate extremes may lower crop yields beyond the impacts of mean climate change. Long-term yields may be affected by the increased occurrence of extreme weather events, which may directly damage crops at crucial developmental stages, or may make the timing of field applications more difficult, reducing the efficiency of farm inputs (Porter and Semenov, 2005, Antle *et al.,* 2004).

- Impacts of climate change on irrigation water requirements may be large. Recent studies have found that there may be a global increase of net crop irrigation requirements of 5-8% by 2070, with considerable regional variation (Döll, 2002). Increases in water stress are projected for the Middle East and south-east Asia (Fischer *et al.,* 2007; Arnell, 2004). These increases in irrigation water requirements may undermine any potential positive effect of CO_2 fertilization.

- Stabilisation of CO_2 concentrations reduces damage to crop production in the long term. Overall impacts on global crop production are projected to be significantly less under lower levels of CO_2 stabilisation (Arnell, 2004; Tubiello and Fischer, 2007) (*i.e.* at 550ppm compared to 750ppm or a BAU scenario). In the first half of this century, some regions may be worse off with mitigation than without, because of lower CO_2 levels and resulting lack of CO_2 stimulation effects on crops (Tubiello and Fischer, 2007).

Synthesis studies: Results of synthesis studies (although containing considerable uncertainty due to discrepancies between the models in precipitation change, poor representation of extreme events, and the assumed strength of CO_2 fertilization), indicate that moderate to medium local increases in temperature (up to 3°C) can have small beneficial impacts on the main cereal crops. However, further warming is expected to have increasingly negative impacts. In low-latitude regions, even moderate temperature increases are likely to have negative yield impacts for major cereal crops. Above 3°C, average impacts are stressful to all crops and in all regions (Easterling *et al.,* 2007). Global production potential, or Net Primary Productivity, may be threatened at +1° local temperature change and is likely to decline beyond 3°C. Precipitation changed may affect production responses beyond the temperature signal.

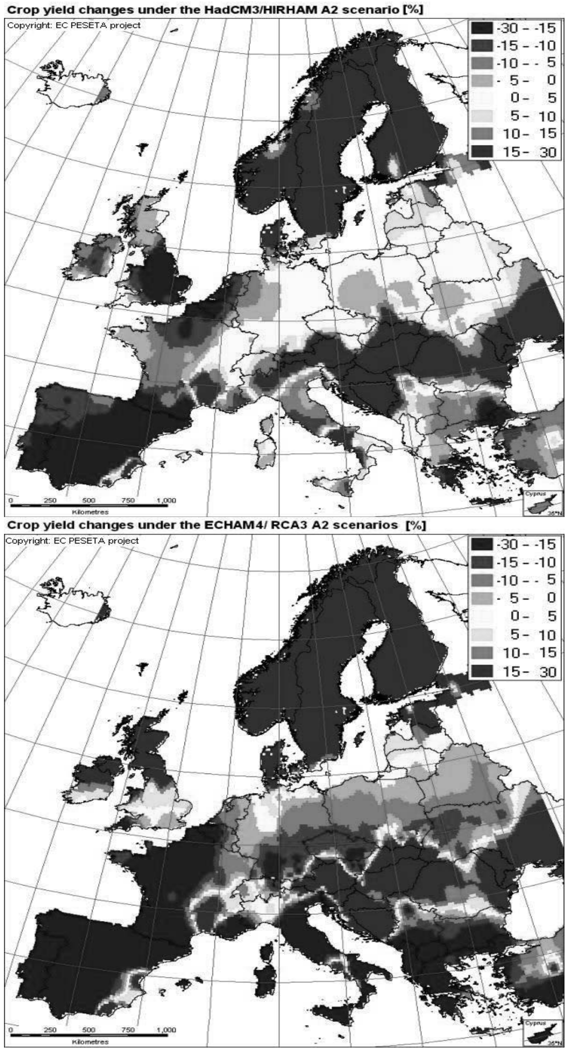
Figure 2.2 shows simulated crop yield changes by 2080s relative to the period 1961-90 according to a high emission scenario (SRES A2 – please refer to Box 3.3 for a description of the scenario) and two different climate models: (upper) HadCM3/HIRHAM; (lower) ECHAM4/RCA3, map elaboration by EC JRC/IES. These figures are produced as part of the PESETA project.[1] The PESETA results assume a relatively optimistic degree of adaptation where farmers can use as much additional irrigation water and/or fertilizers as wished, without any constraint. In these simulations, current land-use patterns are assumed to remain constant until 2085, as are agricultural policies.

The maps provide indications of the general spatial pattern of changes in agriculture yields across Europe. Results for two different global circulation models are presented, using the same socio-economic scenario and GHG emissions. The lower map generally shows larger changes in crop yields than the upper map, due to the different climate conditions.

Considerable research has been carried out on cereals but the effect of climate change on other crops, such as root crops, brassica and millet etc. has not been studied as much. These other crops are of considerable importance to the rural poor in many countries and this is therefore an important area of future research.

[1] http://peseta.jrc.ec.europa.eu/index.html.

Figure 2. 2. Simulated crop yield changes by the 2080s relative to the period 1961-90 according to a high emission scenario (IPCC A2) and two different climate models[1]



Note:

1. Upper: HadCM3/HIRHAM; Lower: ECHAM4/RCA3.

Map elaboration by EC JRC/IES (PESETA).

Source: http://peseta.jrc.ec.europa.eu/index.html.

Pastures and livestock production

It has been known since the third IPCC assessment (TAR) that the combination of increases in CO_2 concentration, together with changes in rainfall and temperature were likely to have significant impacts on grasslands and rangelands, with production generally increasing in humid temperate grasslands, but decreasing in arid and semi-arid regions. Since the TAR research has found that plant community structure is altered by elevated CO_2 and climate change (Easterling *et al.,* 2007). This means there may be rapid changes in species composition and diversity, leading to vulnerability of some species and possible implications for ruminant livestock. Areas that are already colonised by relatively unpalatable plant species (such as upland areas in the United Kingdom) may become even less suitable for grazing at elevated CO_2 levels, as species such as bracken, matt grass and tor grass could become more dominant. This would affect the nutritional value of extensive grasslands to grazing animals (Defra, 2000).

Thermal stress has been shown to decrease productivity and conception rates and is potentially life-threatening to livestock. Models of animal energetics and nutrition (Parsons *et al.,* 2001) have shown that high temperatures put a ceiling on milk production, regardless of feed intake. Increases in air temperature may potentially affect conception rates of animals not adapted to the conditions, particularly cattle. Model results from the United States show reductions in swine, beef and dairy milk production of 1.2%, 2.0%, and 2.2% respectively, for the 2050 scenario using the CGC (version 1) model, and 0.9%, 0.7%, and 2.1% for the HadCM2 model (Mader *et al.,* 2008).

Correspondingly, results since the TAR illustrate that increased climate variability and droughts may lead to livestock loss, both from exposure outdoors and due to poorly adapted housing and transportation methods. Extreme events and weather variability will have a far greater impact on animal productivity than effects associated with average changes in climate. Animals not adapted to weather events may suffer severe losses, particularly those confined in cattle feedlots (Hahn *et al.,* 2001). Additionally, economic losses from reduced cattle performance are estimated to exceed those associated with cattle mortality losses by several-fold (Mader, 2003). However, such a calculation depends on how regulatory standards on housing and transportation in many countries are reviewed to accommodate increased temperature extremes. ENSO events are expected to intensify with climate change, leading to changes in vegetation and water availability (Gitay *et al.,* 2001). Strong relationships exist between drought and animal death, especially in Africa and Mongolia (Easterling *et al.,* 2007). The combination of drought and heat stress in animals is also likely to lead to increased pressure on water resources.

Gradual temperature change, in conjunction with elevated CO_2 levels, is expected to increase grassland productivity in general, with the greatest positive effect expected at high latitudes (Rustad *et al.,* 2008). However, projected decreases in rainfall in some major grassland and rangeland areas may have important implications for productivity and plant species composition. Table 2.2 summarises the impacts on grasslands for different temperature changes.

Industrial crops

The AR4 indicates there is limited knowledge regarding the effects of climate change on industrial crops such as oilseeds, gums and resins, sweeteners, beverages, fibres, and medicinal and aromatic plants. Biofuel crops such as maize and sugarbeet will face similar effects as other crops discussed earlier in this report. Reduced rainfall may cause groundnut yields in Niger to reduce, while there may be large increases in cotton yields due to increases in ambient CO_2 concentration. However, changes in temperature and precipitation may negate these effects (Varaprasa *et al.,* 2003). Perennial industrial crops may be at greater risk than annual crops, as both damages (temperature stresses, pest outbreaks, increased damage from extremes) and benefits may accumulate with time.

Table 2.2. Impacts on grasslands of incremental temperature change

Local temp-erature change	Sub-sector	Region	Impact trends	Sign of impact	Scenario/ Experiment	Source
+0-2° C	Pastures and livestock	Temperate	Alleviation of cold limitation	+	SIM	Parsons *et al.,* 2001
			Increasing productivity		IS92a	Riedo *et al.,* 2001
			Increased heat stress for livestock	–	IS92a	Turn-penny *et al.,* 2001
		Semi-arid and Mediterra-nean	No increase in net primary productivity	0	EXP	Shall *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; Reido *et al.,* 2001
		Temperate	Negative on swine and confined cattle	–	HadCM2, CGCM1	Frank and Dugas, 2001
		Semi-arid and Mediterra-nean	Productivity decline	–	HadCM3 A2 and B2	Howden *et. al.,* 1999

Table 2.2 (continued)

Local temp-erature change	Sub-sector	Region	Impact trends	Sign of impact	Scenario/ Experiment	Source
			Reduced ewe weight and pasture growth. More animal heat stress			Batima *et al.,* 2005
		Tropical	No effect (no rainfall change assumed)	– to 0	EXP	Newman *et al.,* 2001; Volder *et al.,* 2004
			More animal heat stress	–		

Note:
EXP = Experiment; SIM = Simulation without explicit reference to an SRES scenario; GMT = Global mean temperature.

Source: Easterling *et al.,* 2007.

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