Climate change as a driver for European agriculture

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Summary

The studies on anthropogenic climate change performed in the last decade over Europe indicate consistent increases in projected temperature and different patterns of precipitation with widespread increases in northern Europe and rather small decreases over southern Europe. These changes in climate patterns are expected to greatly affect all components of the European agricultural ecosystems (e.g. crop suitability, yield and production, livestock, etc.).

In northern areas climate change may produce positive effects on agriculture through introduction of new crop species and varieties, higher crop production and expansion of suitable areas for crop cultivation. Disadvantages may be an increase in the need for plant protection, the risk of nutrient leaching and depletion of soil organic matter. In southern areas the disadvantages will predominate. The possible increase in water shortage and extreme weather events may cause lower harvestable yields, higher yield variability and a reduction in suitable areas for traditional crops. These effects may reinforce the current trends of intensification of agriculture in Northern and Western Europe and extensification in the Mediterranean and Southeastern parts of Europe.

Adaptation strategies need to be introduced to reduce negative effects and exploit possible positive effects of climate change. Both short-term adjustments (e.g. changes in crop species, cultivars and sowing dates) and long-term adaptations (e.g. land allocation and farming system) should be considered. However, the differences in climate exposure, sensitivity, and adaptive capacity will affect in a different way the agricultural eco-systems across Europe. In particular, agriculture in the Mediterranean region seems to be more vulnerable than in other European regions. This calls for a considerable effort in research and development to deal with the changes, both at the continental and regional levels. European agricultural research and the agroindustry have considerable skills and know-how, which through technology transfer and promotion of innovation could be used for improving adaptive capacity in less well developed regions of the world, which will generally be more severely affected by climate change.

Introduction

Europe is one of the world's largest and most productive suppliers of food and fibre. In 2004 it accounted for 21% of global meat production and 20% of global cereal production. About 80% of this production occurred in the EU25 countries. The productivity of European agriculture is generally high, in particular in Western Europe, and average cereal yields in the EU countries are more than 60% higher than the world average. The EU Common Agricultural Policy has during the last decade been reformed to reduce overproduction, reduce environmental impacts and improve rural development. This is not expected to greatly affect agricultural production in the short run (OECD, 2004). However, agricultural reforms are expected to enhance the current process of structural adjustment leading to larger and fewer farms (Marsh, 2005).

The hydrological features in Europe are very diverse, and there is also a large diversity in water uses, pressures and management approaches. About 30% of abstracted fresh water in Europe is used for agricultural purposes, primarily irrigation (Flörke and Alcamo, 2005). The proportion of fresh water abstraction used for agricultural purposes is only 4% in Northern EU, but as high as 44% in

Southern EU and projected to increase to 53% by 2030 under baseline conditions (Flörke and Alcamo, 2005). Although the quality of river water is improving in most European countries (Nixon et al., 2003), the impact of agriculture on Europe's water resources needs to be reduced if "good ecological" status of surface and ground water is to be achieved as required by the EU Water Framework Directive. There are many pressures on water quality and availability, including those arising from agriculture, industry, urban areas, households and tourism (Lallana et al., 2001). Recent floods and droughts have put additional stresses on water supplies and infrastructure (Estrela et al., 2001).

Agricultural systems are not only sensitive to climate change; they are also among the main contributors to global warming through emissions of several greenhouse gases (primarily CO_2, methane (CH_4) and nitrous oxide (N_2O)). These emissions began long before the use of fossil fuels, and may have contributed to the currently warm global climate compared with the climates usually seen at the end of interglacial periods (Ruddiman, 2003). Currently, agricultural activities are also among the major contributors to total EU greenhouse gas emissions (GHG) (up to 9% in 2000) (EEA, 2002). Thus, mitigation strategies will also be required within the agricultural sector to comply with the reduction targets of the Kyoto Protocol.

Global agricultural systems vary considerably in their sensitivity to climate and in vulnerability to change in the climatic regime. Intensive farming systems in North-western Europe are generally considered to have low sensitivity to climate change, because a given change in temperature or rainfall have modest impact (Chloupek et al., 2004), and because the farmers have resources to adapt and compensate by changing management. These systems may therefore respond favourably to a modest climatic warming (Olesen and Bindi, 2002). On the other hand some of the low input farming systems currently located in marginal areas may be most severely affected by climate change (Reilly and Schimmelpfennig, 1999; Darwin and Kennedy, 2000). In particular an increase in extreme events of both temperature and rainfall will affect the vulnerability of European agroecosystems to climatic conditions.

Climate change is expected to affect agriculture very differently in different parts of the world (Parry et al., 2004). The resulting effects depend on current climatic and soil conditions, the direction of change and the availability of resources and infrastructure to cope with change. There is a large variation across the European continent in climatic conditions, soils, land use, infrastructure, political and economic conditions (Bouma et al., 1998). These differences are expected also to greatly influence the responsiveness to climatic change (Olesen and Bindi, 2002).

The economic consequences may be considerable on a global scale, and it has recently been estimated that the costs of climate change greatly exceed the costs associated with reducing greenhouse gas emissions (Stern, 2006). However, the emissions and the related consequences occur on very different timescales, making economic evaluations difficult not only due to uncertainties in predictions of climate changes and impacts, but also due to uncertainties in the costs of technologies to mitigate change. Taking proper action on mitigating and adapting to climate change also requires long lead times, which have impacts on the way related policies are devised and implemented.

This paper briefly described the impacts of climate change on European agricultural systems, and further discusses how agriculture in Europe may adapt to climate change and how this may influence European agricultural policy. Agriculture is also a significant emitter of greenhouse gases, and the need and possibilities for reducing emissions are briefly described.

Observed climatic changes in Europe

Most of Europe has experienced increases in surface air temperature during the 20th century, which amounts to 0.8 °C in annual mean temperature over the entire continent (Kjellström, 2004; Schär et al., 2004). However, the recent period shows a trend considerably higher than the mean trend (+0.4°C/decade for the period 1977-2001, Jones and Moberg, 2003). For the past 25 years, trends are higher in Central, northeastern Europe and in mountainous regions, while the lowest temperature trends are found in the Mediterranean region (Klein Tank, 2004). Temperatures are increasing more in winter than summer (EEA, 2004; Jones and Moberg, 2003). An increase of temperature variability has been observed, primarily due to increase in warm extremes (Klein Tank and Können, 2003).

There are indications of changes in the rainfall pattern as indicated by the frequency of drought events during spring and early summer (Fig. 1). There has been an increase in frequency of droughts in large parts of Western and Eastern Europe, with particularly large increases in the Mediterranean region. Mean annual precipitation is increasing in most of Atlantic- and Northern Europe and decreasing along the Mediterranean (Klein Tank et al., 2002). An increase in mean precipitation per wet day has been observed in most parts of the continent, even in areas getting drier (Frich et al., 2002; Klein Tank et al., 2002).

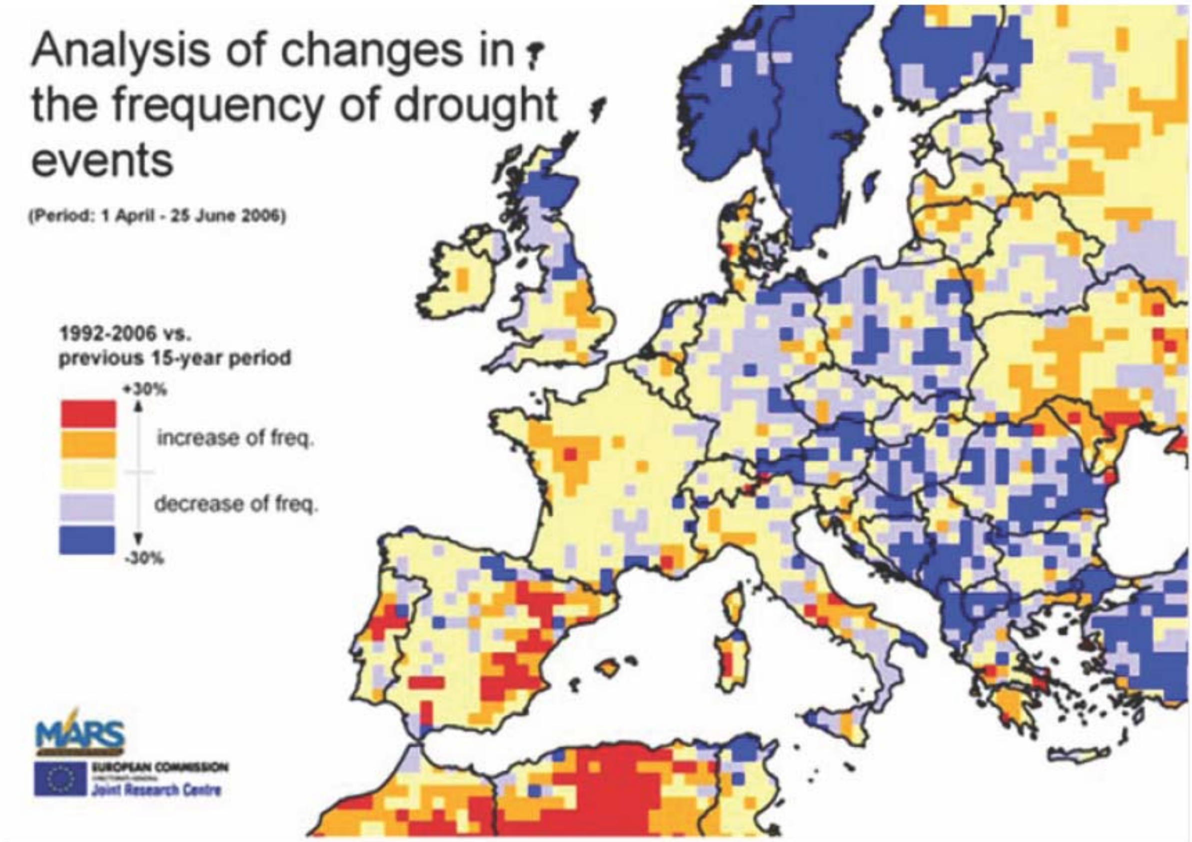


Fig. 1. Observed changes in frequency of drought events in Europe for the period 1992-2006 compared with 1977 to 1991 (data from EC-JRC Ispra).

The changes in particular in temperature have led to observed changes in the performance of agroecosystems (Table 1). Most of these observed changes reflect a change towards a warmer mean climate.

Agroecosystems respond not only to changes in mean climate, but also to changes in frequency of extreme events (Porter and Semenov, 2005). Two such extreme events over the past ten years may be taken as examples of change in frequency of extreme climate events: the flooding in Central Europe in 2002, and the heat wave in Southern and Central Europe in 2003.

Table 1. Observed climate related changes in European agroecosystems during the latter part of the 20th century.

Region	Observed change	Reference
Eurasia	Lengthening of growing season by 1 day/decade	Zhou et al. (2001)
Britian Southern Scandinavia	Increased area of silage maize	Olesen and Bindi (2004)
Finland	Advance of potato planting	Hilden and Lehtonen (2005)
France	Increase in growing season of grapevine and changes in wine quality	Duchene and Scheider (2005) Jones and Davis (2000)
France	Advance of maize sowing dates by 20 days	Benoit and Torre (2004)
Germany	Advance in flowering of winter rye	Chmielewski et al. (2004)
Germany	Advance in flowering of fruit trees	Menzel (2003)

Severe flooding affected parts of Austria, the Czech Republic and Germany for three weeks during August 2002. Heavy rainfall from storms crossing central Europe during early August triggered sequential flood waves that moved down the Vltava, Labe and Elbe rivers in the Czech Republic and Germany, and down the Danube river in Austria, Slovakia, Hungary, Croatia, Serbia and Romania. Estimated economic damages exceeded 15 billion Euro in the Czech Republic and Germany alone, of which only about 15% was insured (RMS, 2003). The rainstorms that led to the August 2002 flooding events have generally been successfully simulated using high-resolution climate models (Zangl, 2004). Recent results using high-resolution regional climate models have shown that global warming may be linked with a shift towards heavier intensive summertime precipitation over large parts of Europe (Christensen and Christensen, 2003). The precipitation events over central Europe may therefore occur more frequently in the future (Pal et al., 2004). The severity of the floods was probably enhanced by human management of the river systems, e.g. diking and installation of reservoirs (Helms et al., 2002) and possibly by the agricultural land use in the river basins (van der Ploeg and Schweigert, 2001). There are thus several management options to reduce the risk of floods in European river systems (Hooijer et al., 2004).

A severe heat wave over large parts of Europe in 2003 extended from June to mid-August, raising summer temperatures by 3 to 5 °C. The warm anomalies in June lasted throughout the entire month (increases in monthly mean up to 6-7°C), but July was only slightly warmer than on average (1-3°C), and the highest anomalies was reached between 1 and 13 August (+7 °C) (Fink et al., 2004). Maximum temperatures of 35 to 40 °C were repeatedly recorded in most Southern and Central European countries (André et al., 2004; Beniston and Diaz, 2004). This heat wave has been found to be extremely unlikely statistically under current climate (Schär and Jendritzky, 2004). However, it is consistent with a combined increase in mean temperature and temperature variability (Schär et al., 2004; Meehl and Tebaldi, 2004; Pal et al., 2004). As such the 2003 heat wave resembles simulations by regional climate models of summer temperatures in the latter part of the 21st century under the A2 scenario (Beniston, 2004; Beniston and Diaz, 2004). The heat wave was associated with annual precipitation deficits up to 300 mm, and this drought was a major contributor to the estimated reduction of 30% over Europe in gross primary production of terrestrial ecosystems (Ciais et al., 2005). This reduced agricultural production and increased production costs, giving an estimated damage of 13 billion euros (Fink et al., 2005). The hot and dry conditions led to many large wildfires, in particular in Portugal, where 390.000 ha were affected (Fink et al., 2004). Many major rivers (e.g. Po, Rhine and Loire) were at record low levels, resulting in disruption of irrigation (Beniston and Diaz, 2004).

Emissions scenarios and land use change

The evaluation of climate change is usually based on simulations with global climate models (GCM) for the IPCC emissions scenarios (SRES scenarios), which describe very different socio-economic futures (Houghton et al., 2001). The SRES scenarios are grouped into four different categories (A1: world markets, A2: provincial enterprise, B1: global sustainability, B2: local stewardship). The grouping relies upon two orthogonal axes, representing social values (ranging from consumerist to conservationist) and level of governance (ranging from local to global), respectively.

The SRES scenarios for socio-economic development have been adapted to European conditions (Parry, 2000; Holman et al., 2005; Abildtrup et al., 2006), and their main characteristics are outlined in Table 2. Assumptions about future European land use and the environmental impact of human activities depend greatly on the development and adoption of new technologies. For the SRES scenarios it has been estimated that increases in crop productivity relative to 2000 could range between 25 and 163% depending on the time slice (2020 to 2080) and scenario (Ewert et al., 2005). These increases were smallest for the B2 and highest for the A1FI scenario.

Table 2. Adaptation of SRES scenarios to Europe (Parry, 2000; Rounsevell et al., 2005, 2006; Abildtrup et al., 2006).

Scenario	Characteristics for Europe
A1. World market	Emphasis on pursuing economic growth and free trade
	European economic inequalities eradicated and rising income levels
	Stable political and social climate with good health care and education
	EU enlargement to include new member states
	EU is a single market, functionally integrated with other markets
A2. Provincial enterprise	Society is dictated by short-term consumerist values
	Policy decisions are taken at national and sub-national levels
	Europe adopts protectionist economic and trade policies
	Declining equity between European countries
	EU competences remain as they are today and enlargement is restricted
B1. Global sustainability	Emphasis on international solutions to global environmental problems
	Enlargement of the EU and development towards a federal structure
	EU takes over responsibility to solve environmental problems
	International institutions will adopt social programmes
B2. Local sustainability	Focus on solving environmental problems locally (green technologies)
	In EU the principle of subsidiarity shifts governance to the local level
	The enlargement and the deepening of EU is abandoned
	Decisions are often taken at subnational levels
	Europe is more heterogeneous, including larger differences in regional incomes

Temporally and spatially explicit future scenarios of European land use have been developed for the four core SRES scenarios (Schröter et al., 2005; Rounsevell et al., 2006). These scenarios are based on supply/demand models of market forces, rural development and environmental policies based on qualitative descriptions in the scenarios and the characteristics of the European landscapes. The results show large declines in agricultural land area resulting from the assumptions about future crop yield with respect to changes in demand for agricultural commodities (Rounsevell et al., 2005). Expansion of urban area is similar between the scenarios, whereas forest areas increase in all scenarios (Schröter et al., 2005). The scenarios showed decreases in European cropland for 2080 that ranged from 28% to 47% (Rounsevell et al., 2005). The reduction in European grassland for 2080 ranged from 6% to 58%. This decline in agricultural area will make land resources available for other uses such as biofuel production and nature reserves. However, over the shorter term (up to 2030) overall changes in agricultural land use may be small (van Meijl et al., 2006), although specific regions may be severely affected (Schröter et al., 2005).

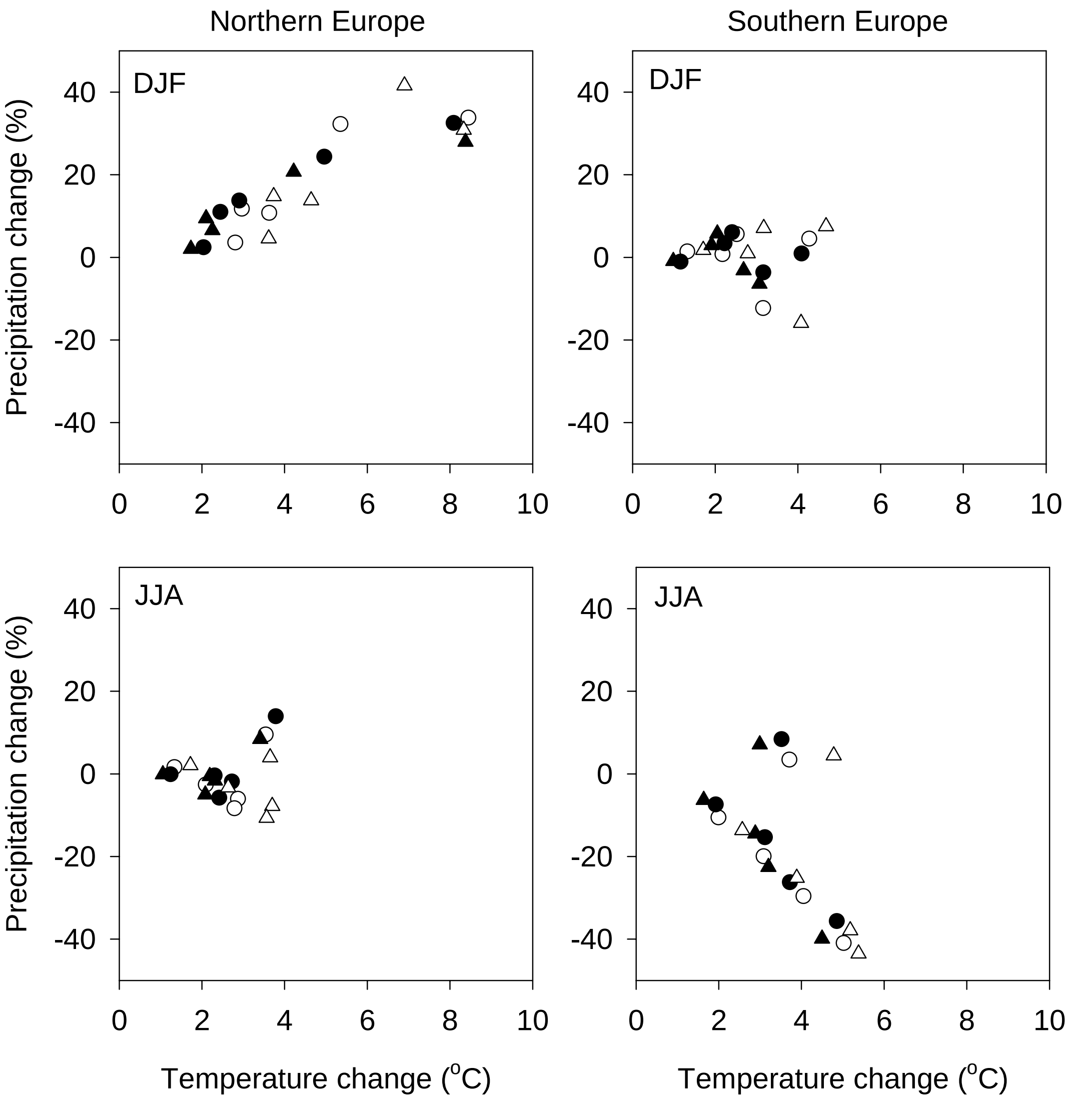
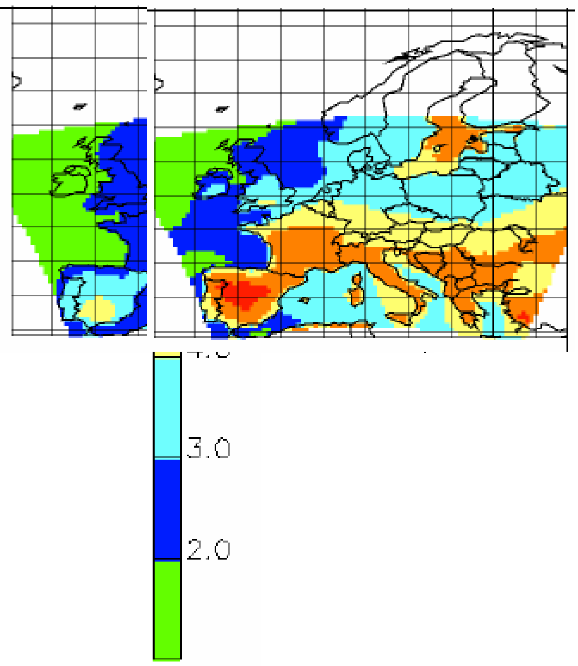


Fig. 2. Projected climate change by 2040-2069 relative to the baseline period 1961-1990 depicted as mean relative change in precipitation versus temperature change for the winter (December to February, DJF) and summer (July to August, JJA) periods for Northern and Southern Europe. The points represent simulated results of different coupled atmosphere-ocean models driven by four different IPCC SRES scenarios: A1 (Δ), A2 (○), B1 (▲) and B2 (●) (Ruosteenoja et al., 2003).

Spring (MAM) Summer (JJA)



Autumn (SON) Winter (DJF)

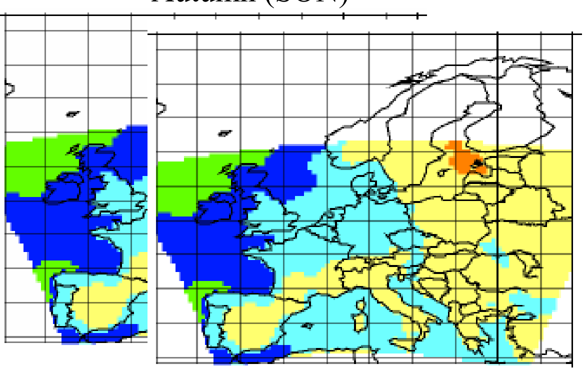
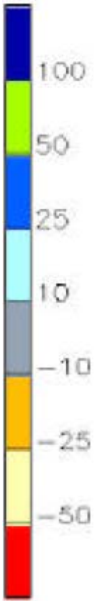


Fig. 3. Projected changes in mean temperature (°C) over Europe for each of the four seasons for 2071-2100 for the A2 emission scenario estimated by a range of RCMs driven by the HadAM3 GCM (Christensen and Christensen, 2006).

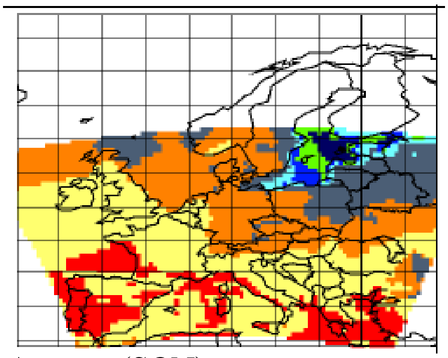
Scenarios of climate change

Most of the recent global climate model (GCM) experiment results are based on coupled ocean-atmosphere models (AO-GCM). The main modelling uncertainties stem from the contrasting behaviour of different climate models in their simulation of global and regional climate change. These uncertainties are largely a function of the relative coarse resolution of the models and the different schemes employed to represent important processes in the atmosphere, biosphere and ocean. There has recently been an increased effort in downscaling the coarse GCM results using regional climate models with spatial resolutions of 50 km or less (Christensen and Christensen, models with spatial resolutions of 50 km or less (Christensen and Christensen, 2006). This has led to improved quality in projections of regional climate changes in Europe (Figs. 3 and 4).

The results of GCM simulations based on the SRES scenarios indicate that annual temperatures over Europe warm at a rate of between 0.1°C decade^{-1} and 0.4°C decade^{-1} (Fig. 2). The projected temperature increases are highest in Northern Europe during winter and highest in Southern Europe during summer. The general pattern of future changes in annual precipitation over Europe is for widespread increases in northern Europe (between +1 and +2 per cent decade^{-1}) and rather small decreases over southern Europe (maximum -1 per cent decade^{-1}).

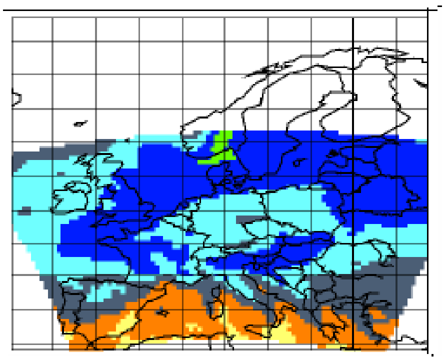


Spring (MAM)



Summer (JJA)

Autumn (SON)



Winter (DJF)

Fig. 4. Projected changes in mean rainfall (% change) over Europe for each of the four seasons for 2071-2100 for the A2 emission scenario estimated by a range of RCMs driven by the HadAM3 GCM (Christensen and Christensen, 2006).

There are marked seasonal and regional differences in the projected changes (Figs. 3 and 4). The warming is greatest over Eastern Europe during winter and over Western and Southern Europe in June-July-August (Giorgi et al., 2004). A very large increase in summer temperatures is projected in the southwestern parts of Europe (exceeds 6 °C in parts of France and the Iberian Peninsula) by the end of the 21st century under the A2 scenario (Fig. 3).

Generally for all scenarios, the mean annual precipitation increases in Northern Europe and decreases further south (Fig. 4). But the change in precipitation varies substantially from season to season and across regions. There is a projected increase in winter precipitation in Northern and Central Europe, whereas there is a substantial decrease in summer precipitation in Southern and Central Europe, and to a lesser extent in Northern Europe.

Recent results indicate that variability in temperature and rainfall may increase considerably over large parts of Central Europe (Christensen and Christensen, 2002; Schär et al., 2004). Indeed heat waves and droughts similar to the 2003 situation may become the norm in central and southern Europe by the end of the 21st century (Beniston and Diaz, 2004). This heat wave led to substantial reductions in primary productivity of terrestrial ecosystems and large and widespread reductions in farm income (Fink et al., 2004; Ciais et al., 2005).

Key vulnerabilities and sensitivities

Biophysical processes of agroecosystems are strongly affected by environmental conditions. The projected increase in greenhouse gases will affect agroecosystems either directly (primarily by increasing photosynthesis at higher CO_2 (Drake et al., 1997)) or indirectly via effects on climate (e.g. temperature and rainfall affecting several aspects of ecosystem functioning (Olesen and Bindi, 2002)) (Table 3). The exact responses depend on the sensitivity of the particular ecosystem and on the relative changes in the controlling factors.

Many studies have assessed effects of climate change on agricultural productivity in Europe (e.g. Harrison et al., 2000; Maracchi et al., 2005). However, relatively little work has been done to link these results across sectors to identify vulnerable regions and farming systems (Olesen and Bindi, 2002). Such assessments are needed to properly identify needs for change in agricultural policy caused by climate change.

Table 3. Influence of CO_2, temperature, rainfall and wind on various components of the agroecosystem.

Component	Influence of factor		
	CO_2	Temperature	Rain/wind
Plants	Dry matter growth Water use	Growth duration	Dry matter growth
Animals	Fodder yield	Growth and reproduction	Health
Water	Soil moisture	Irrigation demand Salinization	Groundwater
Soil	SOM turnover	SOM turnover Nutrient supply	Wind- and water erosion
Pests/diseases	Quality of host biomass	Generation time Earliness of attack	Disease transmission
Weeds	Competition	Herbicide efficacy	

Crop production

Increasing atmospheric CO_2 concentration stimulates yield of C_3 crops and to a lesser extent C_4 crops (Fuhrer, 2003). However, recent estimates of the yield benefit from increasing CO_2 are smaller than earlier ones (Ainsworth and Long, 2005), and the average annual increase of the next decades is marginal compared with what has been achieved through conventional crop management and breeding (Amthor, 1998). Some model studies of CO_2 effects are based on results from enclosure studies from the 1980's, which exaggerate the effects of increased CO_2 on plant production (Long et al., 2006). These model predictions should be considered with caution, since they may substantially overestimate the positive yield effects of increased CO_2.

Increasing temperature affects crops primarily via plant development. With warming, the start of active growth is advanced, plants develop faster, and the potential growing season is extended. This may have the greatest effect in colder regions. However, increased temperature reduces crop duration. In wheat, an increase by 1 °C during grain fill reduces the length of this phase by 5%, and yield declines by a similar amount (Olesen et al., 2000). Maize and soybean yields in the United States between 1982 and 1989 decreased by 17% with each 1 °C increase in growing season mean temperature (Lobell and Asner, 2003). Compared to temperate crops, sensitivity to warming may be even greater in tropical crops because they operate already close to the optimum. In contrast, temperate crops are often temperature-limited and a mild warming (<3 °C) may have a net positive effect, provided that precipitation is sufficient (Easterling and Apps, 2005).

Arable crops

A climatic warming will expand the area of cereals cultivation (e.g. wheat and maize) northwards (Kenny et al., 1993; Carter et al., 1996). For wheat, a rise in temperatures will lead to a small yield reduction, which often will be more than counterbalanced by the effect of increased CO_2 on crop photosynthesis. The combination of both effects will for a moderate climate change lead to moderate to large yield increases in comparison with yields simulated for the present situation (Ghaffari et al., 2002; van Ittersum et al., 2003). Drier conditions and increasing temperatures in the Mediterranean region and parts of Eastern Europe may lead to lower yields there and the adoption of new varieties and cultivation methods. Such yield reductions has been estimated for Eastern Europe, and the yield variability may increase, especially in the steppe regions (Sirotenko et al., 1997). Potato, as well as other root and tuber crops, has shown a large response to rising atmospheric CO_2 (Kimball et al., 2002). On the other hand warming may reduce the growing season in some species and increase water requirements with consequences for yield. Climate change scenario studies performed using crop models show no consistent changes in mean potato yield (Wolf and van Oijen, 2003). For sugar beet yield the increasing occurrence of summer droughts may severely increase yield variability (Jones et al., 2003).

Climate-related increases in crop yields are only expected in Northern Europe, while the largest reductions are expected around the Mediterranean and in the Southwest Balkans and in the South of European Russia (Olesen and Bindi, 2002; Maracchi et al., 2005; Alcamo et al., 2006). In Southern Europe, particularly large decreases in yield are expected for spring-sown crops (e.g. maize, sunflower and soybeans) (Audsley et al., 2006; Moriondo et al., 2006). Whilst, on autumn-sown crops (e.g. winter and spring wheat) the impact is more geographically variable, yield is expected to strongly decrease in the most southern areas and increase in the northern or cooler areas (e.g. northern parts of Portugal and Spain) (Olesen et al., 2006a; Moriondo et al., 2006; Santos et al., 2002). However, these results vary between SRES scenarios and climate models (Olesen et al., 2006a). Some crops that currently grow mostly in Southern Europe (e.g. maize, sunflower and soybeans) will become more suitable further north or in higher altitude areas in the south (Audsley et al., 2006). The projections for a range of SRES scenarios show a 30 to 50% increase in suitable area for grain maize production in Europe by the end of the 21st century, including Ireland, Scotland, Southern Sweden and Finland (Hildén et al., 2005; Olesen et al., 2006a). Moreover, by 2050 energy crops show a northward expansion in potential cropping area, but a reduction in suitability in Southern Europe (Schröter et al., 2005).

Perennial crops

Many fruit trees are susceptible to spring frosts during flowering. A climatic warming will advance both the date of the last spring frosts and the dates of flowering, and the risk of damage to flower buds caused by late frost are likely to remain largely unchanged (Rochette et al., 2004). Additionally the risk of damage to fruit trees caused by early autumn frosts is likely to decrease. However, there may very well be increased problems with pests and diseases (Salinari et al., 2006).

Grapevine is a woody perennial plant, which requires relatively high temperatures. A climatic warming will therefore expand the suitable areas northwards and eastwards (Jones et al., 2005). However, in the current production areas the yield variability (fruit production and quality) may be higher under global change than at present. Such an increase in yield variability would neither guarantee the quality of wine in good years nor meet the demand for wine in poor years, thus implying a higher economic risk for growers (Bindi et al., 1996). However, yields in grapevine may be strongly stimulated by increased CO_2 concentration without causing negative repercussions on the quality of grapes and wine (Bindi et al., 2001). A climatic warming is also likely to lead to unsuitable conditions for currently economically important traditional varieties, at least at their current locations.

Olive is a typical Mediterranean species that is particularly sensitive to low temperature and water shortage, thus both the northern and southern limits of cultivation are conditioned by the climate. The area suitable for olive production in the Mediterranean basin may increase with climate warming (Bindi et al., 1992).

Several perennial crops are candidates for bioenergy crops (Sims et al., 2006). This includes willow for coppice and reed canary grass and Miscanthus for solid biofuel crops to be used in providing biomass for fuel in combined heat and power plants (Clifton-Brown et al., 2004) or for use in second generation bioethanol production (Farrell et al., 2006). The climatic suitability for many of these perennial bioenergy crops is projected to increase over most of Europe for the 21st century (Tuck et al., 2006).

Grasslands

Grasslands will differ in their response to climate change depending on their type (species, soil type, management). In general, intensively managed and nutrient-rich grasslands will respond positively to both the increase in CO_2 concentration and to a temperature increase, given that water supply is sufficient (Thornley and Cannell, 1997). Nitrogen-poor and species-rich grasslands, which are often extensively managed, may respond differently to climate change and increase in CO_2 concentration, and the short-term and long-term responses may be completely different (Cannel and Thornley, 1998). Climate change is likely to alter the community structure of grasslands (Buckland et al., 2001; Lüscher et al., 2004), in ways specific to their location and type, and these changes will often depend on complex interactions between soils, plants and animals. Management and species-richness of grasslands may increase their resilience to change (Duckworth et al., 2000).

Fertile, early succession grasslands have been found to be more responsive to climate change than more mature and/or less fertile grasslands (Grime et al., 2000). In general, intensively managed and nutrient-rich grasslands will respond positively to both increased CO_2 concentration and temperature, given that water and nutrient supply is sufficient (Lüscher et al., 2004). As a general rule, productivity of European grassland is expected to increase (Byrne and Jones, 2002; Kammann et al., 2005).

Livestock

Climate and CO_2 effects influence livestock systems through both availability and price of feed and through direct effects on animal health, growth, and reproduction (Fuquay, 1989).

The impacts of changes in feed-grain prices or the production of forage crops are generally moderated by market forces (Reilly, 1994). However, effects of climate change on grasslands will have direct effects on livestock living on these pastures. Results from a simulation study suggest that the impact on milk production for grass-based systems in Scotland would vary depending on the locality. Conversely, for herds grazing on grass-clover swards milk output may increase regardless of site, when the concentration of CO_2 is enhanced (Topp and Doyle, 1996).

For animals, higher temperatures results in greater water consumption and more frequent heat stress (Turnpenny et al., 2001), which causes declines in physical activities, including eating and grazing. Maintenance requirements are increased and voluntary feed intake is decreased at the expense of growth, milk production and reproduction (Mader et al., 2002). Livestock production may therefore be negatively affected in the warm months of the currently warm regions of Europe (Klinedienst et al., 1993; Mader and Davis, 2004). Warming during the cold period for cooler regions may on the other hand be beneficial due to reduced feed requirements, increased survival, and lower energy costs. Impacts will probably be minor for intensive livestock systems (e.g. confined dairy, poultry and pig systems) because climate is controlled to some degree.

An increase in the frequency of severe heat stress in Britain is expected to enhance the risk of mortality of pigs and broiler chickens grown in intensive livestock systems (Turnpenny et al., 2001). Increased frequency of droughts along the Atlantic coast (e.g. Ireland) may reduce the productivity of grasslands such that they are no longer sufficient for livestock (Holden and Breton, 2002). Increasing temperatures may also increase the risk of livestock diseases by (i) increasing the diffusion of insects (e.g. *Culicoides imicola*) that are the main vectors of several arboviruses (e.g. bluetongue, BT and African horse sickness, AHS); (ii) increasing the survival of viruses from one year to the next; (iii) improving conditions for new insect vectors that are now limited by colder temperatures (Wittmann and Baylis, 2000; Mellor and Wittmann, 2002; Colebrook and Wall, 2004; Gould et al., 2006).

Climate change will also affect the turnover and losses of nutrients from animal manure, both in houses, storages and in the field. Examples of this is the increase in ammonia volatilisation with increasing temperature (Sommer and Olesen, 2000; Sommer et al., 2003), and the increase in methane emissions from manure slurry tanks with increasing temperature (Sommer et al., 2004).

Weeds, pests and diseases

The majority of the pest and disease problems are closely linked with their host crops. This makes major changes in plant protection problems less likely (Coakley et al., 1999).

Conditions are more favourable for the proliferation of insect pests in warmer climates, because many insects can then complete a greater number of reproductive cycles (Bale et al., 2002). Warmer winter temperatures may also allow pests to overwinter in areas where they are now limited by cold, thus causing greater and earlier infestation during the following crop season. Insect pests are also affected directly by the CO_2 effect through the amount and quality of the host biomass (Cannon, 1998). Climate warming will lead to earlier insect spring activity and proliferation of some pest species (Alig et al., 2004; Cocu et al., 2005). A similar situation may be seen for plant diseases leading to an increased demand for pesticide control (Salinari et al., 2006).

Unlike pests and diseases, weeds are also directly influenced by changes in atmospheric CO_2 concentration. Higher CO_2 concentration will stimulate growth and water use efficiency in both C_3 and C_4 species (Ziska and Bunce, 1997). Differential effects of CO_2 and climate changes on crops and weeds will alter the weed-crop competitive interactions, sometimes for the benefit of the crop and sometimes for the weeds. However, interaction with other biotic factors may also influence weed seed survival and thus weed population development (Leishman et al., 2000).

Changes in climatic suitability will lead to invasion of weed, pest and diseases adapted to warmer climatic conditions (Baker et al., 2000). The speed at which such invasive species will occur depends on the change of climatic change, the dispersal rate of the species and on measures taken to combat non-indigenous species (Anderson et al., 2004). The dispersal rate of pests and diseases are most often so high that their geographical extent is determined by the range of climatic suitability (Baker et al., 2000). The Colorado beetle, the European cornborer, the Mediterranean fruit fly and karnal bunt are examples of pests and diseases, which are expected to have a considerable northward expansion in Europe under climatic warming.

Environmental impacts

Environmental impacts of agriculture under a changing climate are becoming more and more important. In particular, the role of nitrate leaching on the quality of aquifers, rivers and estuaries is globally recognized (Galloway, 2004). A warming is expected to increase soil organic matter turnover provided sufficient water is available, and experiment have shown that increases in net N mineralisation rates may be considerably higher than the increases in soil respiration (Rustad et al., 2001).

Projections made at European level for winter wheat showed for the 2071-2100 time-slice that decreases in N-leaching predominate over large parts of Eastern Europe and some smaller areas in Spain, whereas increases occur in the UK and in smaller regions over many other parts of Europe (Olesen et al., 2006a). This in combination with longer growing seasons for the aquatic ecosystems would likely lead to higher risk of algal blooms and increased growth of toxic cyanobacteria in lakes (Moss et al., 2003; Eisenreich, 2005).

The climate change scenarios could also lead to increases in GHG emissions from agriculture. Increasing temperatures will speed decomposition where soil moisture allows (Davidson and Janssens, 2006), so direct climate impacts on cropland and grassland soils will tend to decrease SOC stocks for Europe as a whole (Smith et al., 2006). This effect is greatly reduced by increasing C inputs to the soil because of enhanced NPP, resulting from a combination of climate change and increased atmospheric CO_2 concentration. However, decomposition becomes faster in regions where temperature increases greatly and soil moisture remains high enough to allow decomposition (e.g. North and East Europe), but does not become faster, where the soil becomes too dry, despite higher temperatures (Southern France, Spain, and Italy) (Smith et al., 2006).

Extreme events and climatic variability

Extreme weather events, such as spells of high temperature, heavy storms, or droughts, can severely disrupt crop production. Individual extreme events will not usually have lasting effects on the agricultural system. However, when the frequency of such events increases agriculture needs to respond, either in terms of adaptation or abandonment.

Crops often respond nonlinearly to changes in their growing conditions and have threshold responses, which greatly increases the importance of climatic variability and frequency of extreme events for yield, yield stability and quality (Porter and Semenov, 2005). Thus an increase in temperature variability will increase yield variability and also result in a reduction in mean yield (Trnka et al., 2004). Therefore the projected increases in temperature variability over Central and Southern Europe (Schär et al., 2004) may have severe impacts on the agricultural production in this region.

In addition to the linear and nonlinear responses of crop growth and development to variation in temperature and rainfall, short-term extreme temperatures can have large yield-reducing effects (Porter and Gawith, 1999; Wheeler et al., 2000). This is particular the case during flowering and fruiting periods, where short-term exposure to high temperatures (usually above 35 °C; Porter and Semenov, 2005) can greatly reduce fruit set and therefore yield. Exposure to drought during these periods may have similar effects.

Adaptation to climate change

To avoid or at least reduce negative effects and exploit possible positive effects, several agronomic adaptation strategies for agriculture have been suggested. Studies on the adaptation of farming systems to climate change need to consider all the agronomic decisions made at the farm level (Kaiser et al., 1993). Economic considerations are very important in this context (Antle, 1996). Results of farm level analyses on the impact and adaptation to climate change have generally shown a large reduction in adverse impacts when adaptation is fully implemented (Mendelsohn and Dinar, 1999). This often implies changes in agricultural land use (Darwin, 2004; Rounsevell et al., 2006).

The agronomic strategies available include both short-term adjustments and long-term adaptations. (Easterling, 1996). Most of the short-term adjustments in involve relatively little cost to the farmers, since they are often just extensions of the existing schemes to deal with climatic variability. However, long-term adaptations and changes in farming systems, institutions, land use etc. may carry considerably higher costs. Some of these costs can be reduced, if timely action is taken (Stern, 2006). However, there is a need at regional, national and international levels to analyse the needs for such planned adaptation options, their costs and their time horizon.

Most adaptations to climate change are triggered by extreme or rare weather events, in particular when these events become recurrent. It is therefore important to be aware not only of changes in mean climatic conditions, but also of changes in climatic variability and extreme weather events.

Autonomous adaptations

The short-term adjustments include efforts to optimise production without major system changes. They are autonomous in the sense that no other sectors (e.g. policy, research, etc.) are needed in their development and implementation. Examples of short-term adjustments are changes in varieties, sowing dates and fertiliser and pesticide use (Ghaffari et al., 2002; Alexandrov et al., 2002; Tubiello et al., 2000; Chen and McCarl, 2001). In particular, in Southern Europe short-term adaptations may include changes in crop species (e.g. replacing winter with spring wheat cultivars grown during winter and spring) (Minguez et al., 2006), changes in cultivars and sowing dates (e.g. for winter crops, sowing the same cultivar earlier, or choosing cultivars with longer crop cycle; for summer irrigated crops, earlier sowing for preventing yield reductions or reducing water demand) (Olesen et al., 2006a). There are many plant traits that may be modified to better adapt varieties to increased temperature and reduced water supply (Sinclair and Muchow, 2001). However, the effectiveness of such traits depend on whether there is simultaneous change climatic variability, and a combination of traits may be needed to stabilise yield in poor years, without sacrificing yield in good years (Porter et al., 1995; Sinclair and Muchow, 2001). In Northern Europe new crops and varieties may be introduced only if improved varieties will be introduced to respond to specific characteristics of the growing seasons (e.g. length of the day) (Hilden et al., 2005).

Long-term adaptations

The long-term adaptations refer to major structural changes to overcome adversity caused by climate change. This involves changes in land allocation and farming systems, breeding of crop varieties, new land management techniques, etc. This involves changes of land use that result from the farmer's response to the differential response of crops to climate change. The changes in land allocation may also be used to stabilise production. This means substitution of crops with high inter-annual yield variability (e.g. wheat or maize) by crops with lower productivity but more stable yields (e.g. pasture or sorghum). Crop substitution may be useful also for the conservation of soil moisture. Long lead times in crop substitution are present for the perennial crops (e.g. grapevine, olive and fruit trees), and here adequate and region specific information on climate change and suitable species and varieties are critical for efficient adaptation. Other examples of long-term adaptations include breeding of crop varieties, new land management techniques to conserve water or increase irrigation use efficiencies, and more drastic changes in farming systems (including land abandonment). Increasing the supply of water for irrigation for irrigation may not be a viable option in much of Southern Europe, since the projections show a considerable reduction in total runoff (Lehner et al., 2006).

Changes in farming systems

The farm is typically the entity at which adaptation to climate change and climatic variability must take place through introduction of new management methods and technologies. Because of the complexities of processes, management and inter-relationships of land use within a farm, studies on farming systems require a holistic approach (Rivington et al., 2006). Climate change will not only affect crop yield, but total farm-level production through effects on altered carbon and nitrogen flows resulting from changed crop and residue quality, crop resource use, or mineralisation of soil organic matter (Drueri et al., 2006). Adaptation will have to deal with all of these issues, and the links with water availability may be among the most important ones, affecting the need for improving irrigation efficiencies (Tavakkoli and Oweis, 2004) or the need for terracing (Wadsworth and Swetham, 1988; Fuhrer et al., 2006).

Recent studies at European level have demonstrated the need to include changes in climate and non-climate factors (technological, socio-economic, etc.) for assessing the changes in crop yield and suitability (Schröter et al., 2005). A different allocation of European agricultural land use seems to represent one of the major long-term adaptation strategies available. Rounsevell et al. (2005) estimate a decline of up to 50% in cropland and grassland areas under the A1FI and A2 scenarios. For the A1FI and A2 scenarios both the quantity and the spatial distribution of crops will change, whilst, for the B1 and B2 scenarios the pressures toward declining agricultural areas should be counterbalanced by policy mechanisms that seek to limit crop productivity.

Changes in farming systems may also play a fundamental role in the adaptation of European agriculture to climate change. The interpretation of four IPCC-SRES scenarios suggests that different types of adaptation of farming systems (intensification, extensification and abandonment) may be appropriate for particular scenarios and areas (high latitude and altitude, marginal areas, etc.) (Berry et al., 2006).

The sensitivity to climate change of farming systems may depend on the degree of diversification. However, based on data from a large number of operations in Canadian prairie agriculture, farms have recently become more specialized, and this trend is unlikely to change in the immediate future (Bradshaw et al., 2004). A similar situation is likely to take place in Europe, although the trend to organic farming in some areas and the urbanization of some rural areas may restrict this development.

Finally, the substitution of food production by energy production through the widespread cultivation of bioenergy crops (Tuck et al., 2006). Several temperate and Mediterranean crop species are suitable for various types of biofuels, including oilseed crops, starch crops, cereals and solid biofuel crops. All climate change scenarios show a northward expansion of these species with Northern Europe becoming more favourable for most species. However, the choice of energy crops in Southern Europe may be severely reduced in future, both due to increased temperatures and reduced rainfall.

Taking in to account both potential impacts and adaptive capacity, the vulnerability of agriculture based on “Farmer livelihood” (profit) have been analysed for EU15 (Metzger et al., 2006). The results show the agricultural sector in the Mediterranean region as vulnerable under most climate change scenarios starting at different time slices, depending on the scenario used. The A1FI and A2 scenarios anticipate greater vulnerability throughout; whilst the B2 scenario seems to be least harmful for farmer livelihood (Metzger et al., 2006).

Changes in policies and institutions

Climate change will impact food production very differently in different parts of the world (Parry et al., 2004). Therefore trade plays an important role in modifying the impacts on world food supply. Indeed global impacts on agriculture and food supply may be small, once the dynamics of economic adjustments and trade are considered (Fischer et al., 2005; Parry et al., 2005). However, several studies have shown that socio-economic drivers such as increased food and feed demand and improvements in production technology and efficiency need to be considered in order to realistically project climate change impacts on food supply (Fischer et al., 2005; Ewert et al., 2005). Without doubt, the trade policies and the associated institutions play a major role in ensuring an efficient adaptation to climate change.

It is indisputable that reforms of European Union agricultural policies will be an important vehicle for encouraging European agriculture to adapt to climate change (Olesen and Bindi, 2002). European agricultural policy increasingly focuses on multifunctionality as its target and its organising principle (Tait, 2001). The concept of multifunctionality requires different interpretation and variable balance among the environmental, social and economic functions in different European regions. Climate change will challenge the current balance between in the basic functions of agriculture in specific regions, and in some cases exacerbate existing regional differences. Agricultural support policies therefore need to adapt a flexible approach based on clear aims for the basic functions of agriculture in different European regions. Under severe climate change scenarios, even these basic functions may have to be re-evaluated, and some traditional European farming systems may have to be changed or abandoned (Olesen and Bindi, 2002).

Other functions of farms and rural areas

Farms do not only function as production units for food, fibre and biomass. They often also serve roles related to services, such as providing a healthy environment, housing for people working in cities and for leisure and tourism. Most of these activities will also be affected by climate change, although these aspects have been studied to a much lesser extent than the effects of climate change on crop production.

Large cities are increasingly causing an urbanisation of the rural areas near such cities (van der Vaart, 2005; Peyrache-Gadeau and Fleury, 2006). Whereas the farm sizes are projected to generally increase due to changes in the agricultural policies and the scale of economics (Marsh, 2005), this may not be the case in the peri-urban areas, where farms serve other important functions than food and fibre production. These rural and peri-urban areas are not a simple periphery determined solely by the town, but have their own priorities and development routes determined by expectations with respect to economic development, environmental and landscape management, cultural aspects etc. (Peyrache-Gadeau and Fleury, 2006). These areas will have vulnerabilities than the distinct rural areas, due to other priorities for the services provided by the agricultural landscape and due to other sensitivities, in particular related to water supply, water quality (Ragab and Prudhomme, 2002) and flood management (Schultz, 2006).

Like agriculture, tourism is closely linked to climate, both in terms of the climate at the source and destination countries of tourists and in terms of climate seasonality, defining the characteristic winter and summer tourism industries (Viner, 2006). For summer tourism, a warming will improve conditions in North and Western Europe (Hanson et al., 2006), and mountainous areas in southern Europe may become more popular due to their relative coolness (Ceron and Dubois, 2000). For the traditional beach tourism along the Mediterranean, a warming may lead to a flattening of the season (Amelung and Viner, 2006). This may give opportunities for other sorts of tourism in rural areas, probably in the more cool regions. For winter tourism, the ski industry in Central Europe is likely to be disrupted by significant reductions in natural snow cover, in particular at the beginning and end of the ski season (Elsasser and Burki, 2002). This may increase the demand for winter tourisms in other areas, e.g. the Scandinavian countries. Another adaptation option for European tourism is promoting other types of tourism, such as ecotourism, which would involve utilising other parts of the rural landscape (Hanson et al., 2006).

Greenhouse gas emissions from agriculture

Agriculture contributed about 9% to EU15 GHG emissions in 2002, excluding changes in soil carbon stocks (EEA, 2005). A major part of these emissions originate from methane (CH_4) and nitrous oxide (N_2O) from livestock, manures and soils.

The intensive carbon and nitrogen cycling on livestock farms may cause these farms to be particularly large sources of both methane and nitrous oxide emissions (Oenema et al., 2005; Olesen et al., 2006b). A large proportion of global (and European) methane and nitrous oxide emissions originate from livestock and the manure produced (Hogan et al., 1991; Lelieveld et al., 1998; Mosier et al., 1998). However, the emissions are greatly affected by both environmental conditions and management, and there most likely is a considerable scope for reducing emissions by improving management and through introduction of new technologies, in particular in feeding and handling of manures (Monteny et al., 2006).

For arable land the most important greenhouse gasses are N_2O and CO_2 (Six et al., 2004) and management practices highly affects the emissions (Robertson et al., 2000; Desjardins et al., 2005). The CO_2 fluxes are affected through the carbon inputs and through tillage, which affect the soil carbon turnover rate by affecting soil organic matter protection. The N_2O fluxes are primarily affected through nitrogen inputs, with excessive N inputs giving particularly large emissions (Chatskikh et al., 2005).

Strategies for reducing emissions from mineral soils have to focus on carbon sequestration, reducing fossil fuel consumption and at the same time reducing N_2O emissions (Freibauer et al., 2004). Carbon sequestration may be accomplished by increasing the carbon input to the soil or by decreasing the turnover rate of organic matter. Emissions of N_2O are primarily related to application of animal manure and mineral fertilizers, nitrate leaching and turnover of residues. Reduced tillage is considered to be one of the most effective management practices for carbon sequestration on arable land (Desjardins et al., 2005). In a comprehensive review, Alvarez (2005) estimated that direct drilling with residue retainment resulted in a long-term (20-30 years) carbon sequestration of 12 t C ha^{-1}.

Organic soils

Northern peatlands sequester carbon and emit methane and thus have both cooling and warming impacts on the climate system through their influence on atmospheric concentrations of CO_2 and CH_4. It has been estimated that the net radiative forcing impact of a northern peatland besing, at peatland formation, as a net warming that peaks after about 50 years, remains a diminishing net warming for hundreds to thousands of years, after which the net cooling impact will increase (Frolking et al., 2006). These effects are modified by temperature and rainfall, which have resulted in varying contributions to global concentrations of CO_2 and CH_4 in the atmosphere since the last glacial period (MacDonald et al., 2006). Climate change effects on net greenhouse gas emissions from Northern peatlands are likely to be mediated primarily through the hydrological cycle, and a drying resulting from altered precipitation patterns and a warmer climate will CH_4 and increase CO_2 emissions from the soil surface (Strack et al., 2006; Trettin et al., 2006). However, methane emissions are to a large extent also influenced by the vegetation type, and climate change may therefore have some secondary effects (Ström et al., 2005; Strack et al., 2006).

In a warming climate, permafrost is likely to be significantly reduced and eventually disappear from the sub-Arctic region. This is likely to significantly increase methane emissions, but may also increase CO_2 absorption (Johansson et al., 2006; Wickland et al., 2006). The terrestrial ecosystems in northern high latitudes will be affected by climate change through several factors, including permafrost melting, CO_2 fertilisation and fire. This is likely to almost double the current carbon emissions from these ecosystems, but these emissions remain relatively small compared with anthropogenic emissions (Zhuang et al., 2006).

Emissions of CO_2 are particularly large from cultivation of organic soils associated with the drainage of such soils (IPCC, 1997), and an effective abatement strategy could be to convert some of these drained peatlands back to wetlands would significantly reduce CO_2 emissions although methane emissions may increase (Merbach et al., 1996).

Mitigation measures in agriculture

The Kyoto Protocol under the UN Framework Convention on Climate Change commits industrialised signatory countries to reduce their emissions to below the level in 1990, and the EU15 countries have a common reduction target for 2008-2012 of 8%. From 1990 to 2003 EU25 GHG emissions decreased by 5.5%, but emissions in the transport sector grew 23% in EU15 (EEA, 2005). There is therefore a continued need to reduce emissions in other sectors, including agriculture. The design of future agricultural production systems and agricultural policies need to consider the need for reductions in GHG emissions. The potential for changes in EU15 agricultural land use to reduce net emissions of CO_2 and N_2O have been estimated at about 8% of the total GHG emissions in these countries (Smith et al., 2000, 2001). However, realistically agricultural soils may be able to sequester less than a fifth of this potential by the Kyoto commitment period in 2008-2012 (Freibauer et al., 2004).

There a number of possibilities for reducing emissions of methane and nitrous oxide emissions through improving management practices and introducing new technologies (Schils et al., 2006; Weiske et al., 2006). Advantage should be taken of the fact that some of the measures simultaneously may reduce the net emission of several greenhouse gases. Such measures may be combined with land management measures to also sequester soil carbon. A number of options exist to reduce or even reverse the emissions of greenhouse gases from agriculture. These options can be grouped according to gases and modes of action:

- Reduction in direct energy use (fuel, electricity, heating) and indirect energy use (e.g. fertilisers).
- Substitution of fossil energy through biofuel production and anaerobic digestion of manure etc (Farrell et al., 2006).
- Increased carbon storage in soils through higher inputs (straw incorporation, manure, cover crops, grass in rotation) and reduced soil organic matter turnover (no-till) (Robertson et al., 2000; Alvarez, 2005; Smith et al., 2000, 2001).
- Reduced methane emissions through improved diets for ruminant animals and through improved handling and storage of manures (including anaerobic digestion) (Moss et al., 2000; Sommer et al. 2004; Monteny et al., 2006).

- Reduced nitrous oxide emissions through tighter nitrogen cycling and through technical measures to reduce emissions from manure stores and from manures and fertilisers applied to soil (Smith et al., 1997; Monteny et al., 2006).

In general, most of these management methods and technologies need to be further developed, if they are to be applied in a cost-effective manner. However, some of these methods provide additional social and environmental benefits, which need to the factored in (Freibauer et al., 2004).

Links between adaptation and mitigation

Many of the options available for adapting agricultural activities will influence the emissions of greenhouse gases either by enhancing or reducing the fluxes. However, it should be kept in mind that agricultural activities affect several greenhouse gases simultaneously, and it is the net effect on the global warming potential of all gases that should be considered. There may also be differences between short- and long-term responses to introduction of system and management changes, in particular for measures that involve changes in soil management and input of carbon and nitrogen to the soil (Six et al., 2004; Ogle et al., 2005). There are very few studies available linking adaptation and mitigation in agriculture, so only a few speculations can be made.

It may be particularly difficult to obtain increases in soil carbon storage or even maintain current stocks, since the global warming will inevitably lead to higher turnover rates of soil organic matter, which will only partly be compensated by increased inputs (Bellamy et al., 2005; Smith et al., 2006).

Several water-conserving practices are commonly used to combat drought. These may also be used for reducing climate change impacts (Easterling et al., 1996). Such practices include conservation tillage, which is the practice of leaving some or all the previous season's crop residues on the soil surface in combination with non-inversion tillage (Holland et al., 2004). This may protect the soil from wind and water erosion and retain moisture by reducing evaporation and increasing the infiltration of rainfall into the soil. These practices also have major impacts on GHG emissions (Robertson et al., 2000).

Irrigation is a commonly proposed adaptation option for coping with increased summer droughts. Irrigation management can be used to improve considerably the utilisation of applied water through proper timing of the amount of water distributed. When irrigation is applied this will increase crop productivity and usually also the amount of crop residues returned to the soil, which will increase carbon sequestration. However, the energy use associated with irrigation can often be a major component of the GHG balance of irrigated systems (Mosier et al., 2005).

Implications for research and development

Research will have to deal with some "unknown aspects" that due to their complexity have not yet been studied in detail. These include the effect on secondary factors of agricultural production (e.g. soils, weeds, pests and diseases), the effect on the quality of crop and animal production, the effect of changes in frequency of isolated and extreme weather events on agricultural production, and the interaction with the surrounding natural ecosystems. It should also be noted that for obvious reasons most studies on climate change impacts have so far focused on crop production. However, some livestock production systems, especially those involving grazing systems or use of fresh fodder, may be severely affected by climate change, and more studies on these systems are warranted.

Crop production in tropical developing countries will suffer more than in most temperate-zone ones, due to a combination of adverse agro-climatic, socio-economic and technological conditions already present today, and their continued poor state in coming decades, compared to developed regions (Alexandratos, 2005). To cope with these changing conditions, there is not only a call for more research to improve the understanding of the underlying mechanisms, but also a need to improve technology transfer from more developed countries, and increasing the local innovation in cropping and farming systems to improve adaptation while improving sustainability and farmer livelihoods. These are areas, where European agricultural research in collaboration with the agroindustry could greatly assist in improving conditions in less developed countries.

There is a considerable need for an increased focus on regional studies of impacts and adaptation to climate change in agriculture, since effects and responses are likely to be regionally specific depending on interactions with soils, current climate and cropping systems (Olesen et al., 2006a). Such studies are now becoming more realistic with the arrival of detailed regional scale climate change scenarios (Christensen and Christensen, 2005). These studies should include assessments of the consequences on current efforts in agricultural policy for a sustainable agriculture that also preserves environmental and social values in the rural society.

There is a need to describe in more detail the needs for research to support adaptation and mitigation to climate change in agriculture. An example of some of the research needs is illustrated for agronomy in Table 4, but similar needs are present for many other fields, including animal science, environmental impact, plant breeding and land use planning.

Table 4. Suggestions for research needs within agronomy proposed at the 9th Congress of the European Society for Agronomy in Warsaw 2006.

Genotypic differences in response to CO_2 and climate changes need to better understood
Improved understanding of secondary effects, e.g. nutrient losses, weeds, pests and diseases, and their interaction with climate and CO_2 change, and inclusion of these effects in crop models
Improved understanding (including experiments) of the effects of extreme events (heat waves, droughts, floods, high intensity rainfall) for the entire agroecosystem functioning
Improved models of climate effects on yield quality
Better models of adaptation options and their applicability at farm and regional scales.
Better understanding on how climate change should be linked with improvements in technology (e.g. biotechnology, tillage, pesticides)
Improved understanding and tools to improve management across sectors (e.g. between the agricultural and the water sector)
Development of models for bioenergy crops and their utilisation
Development of water saving technologies and management practices

The research on adaptation in agriculture has not yet provided a generalised knowledge on the adaptive capacity of agricultural systems across a range of climate and socioeconomic futures. There is also a considerable need to better estimate the costs of various adaptation measures, and adaptation studies have to move from looking at potential adaptation to adoption, taking into account the complexity of farm-level decision-making, diversities at different scales and regions (including the entire food chain), and timelags in responses and biophysical, economic, institutional and cultural barriers to change.

The adaptation to climate change has in particular to be factored in as part of the ongoing technological development in agriculture, including plant breeding (also using molecular techniques), livestock feeding technologies, irrigation management, application of information and communication technology etc. This would be feasible utilising the main agricultural resources (Table 5). In some cases such adaptation measures would make sense without considering climate change, because they help to address current climate variability. In other cases, the measures must be implemented in anticipation of climate change, because they would be ineffective if implemented as a reaction to climate change (Smith and Lenhart, 1996).

Table 5. Suggested resource based policies to support adaptation of European agriculture to climate change (Olesen and Bindi, 2002).

Resource	Policy
Land	*Reforming agricultural policy to encourage flexible land use.* The great extent of Europe cropland across diverse climates will provide diversity for adaptation
Water	*Reforming water markets and raising the value of crop per volume of water used to encourage more prudent use of water*. Water management, that already limits agriculture in some regions, is crucial for adapting to drier climate
Nutrients	*Improving nutrient use efficiencies through changes in cropping systems and development and adoption of new nutrient management technologies.* Nutrient management needs to be tailored to the changes in crop production as affected by climate change, and utilisation efficiencies must be increased, especially for nitrogen, in order to reduce nitrous oxide emissions.
Agrochemicals	*Support for integrated pest management systems (IPMS) should be increased through a combination of education, regulation and taxation.* There will be a need to adapt existing IPMS's to the changing climatic regimes.
Energy	*Improving the efficiency in food production and exploring new biological fuels and ways to store more carbon in trees and soils*. Reliable and sustainable energy supply is essential for many adaptations to new climate and for mitigation policies. There are also a number of options to reduce energy use in agriculture
Genetic diversity	*Assembling, preserving and characterising plant and animal genes and conducting research on alternative crops and animals*. Genetic diversity and new genetic material will provide important basic material for adapting crops species to changing climatic conditions
Research capacity	*Encouraging research on adaptation, developing new farming systems and developing alternative foods.* Increased investments in agricultural research may provide new sources of knowledge and technology for adaptation to climate change
Information systems	*Enhancing national systems that disseminate information on agricultural research and technology, and encourages information exchange among farmers.* Fast and efficient information dissemination and exchange to and between farmers using the new technologies (e.g internet) will speed up the rate of adaptation to climatic and market changes
Culture	*Integrating environmental, agricultural and cultural policies to preserve the heritage of rural environments*. Integration of policies will be required to maintain and preserve the heritage of rural environments which are dominated by agricultural practices influenced by climate

Few studies have so far attempted to link the issue of adaptation and mitigation in agriculture. This is primarily because the issues have so far been dealt with by different research communities and within different policy contexts. However, as both issues are becoming increasingly relevant from a policy perspective, these issues will have to be reconciled. Dealing with these issues requires a interdisciplinary approach, where the research on adaptation in agriculture will need to deal not only with the effects on changes in productivity and economic viability, but also on the related environmental impacts of climate change and adaptation measures. On the other hand the research community dealing with mitigation measures will need to be concerned not only with the efficiencies of mitigation measures, but also with the extent to which these measures and technologies are compatible with changes in climatic conditions and resulting changes in farming systems.

Conclusions

The results of the studies on anthropogenic climate change performed in the last decade over Europe indicate consistent increases in projected temperature and different patterns of precipitation with widespread increases in northern Europe and rather small decreases over southern Europe. These changes in climate patterns are expected to affect all the components of the European agricultural ecosystems (e.g. crop suitability, yield an production, livestock, etc.). Thus, adaptation strategies should be introduced to reduce negative effects and exploit possible positive effects of climate change. Both short-term adjustments (e.g. changes in crop species, cultivars and sowing dates) and long-term adaptations (e.g. water management, land allocation, farming systems and institutions) should be considered. However, the differences in climate exposure, sensitivity, and adaptive capacity will affect in a different way the agricultural eco-systems across Europe. In particular, agriculture in the Mediterranean region seems to be more vulnerable than in other European regions. This calls for a considerable effort in research and development to deal with the changes, both at the continental and regional levels.

References

Abildtrup, J., Audsley, E., Fekete-Farkas, M., Giupponi, C., Gylling, M., Rosato, P., Rounsevell, M.D.A., 2005. Socio-economic scenario development for the assessment of climate change impacts on agricultural land use. Environ. Sci. Pol. 9, 101-115.

Ainsworth, E.A., Long, S.P., 2005. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. New Phytol. 165, 351-372.

Alcamo, J., Döll, P., Heinrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S., 2003. Global estimates of water withdrawals and availability under current and future business-as-usual conditions. Hydrol. Sci. J. 48, 339-348.

Alexandratos, N., 2005. Countries with rapid population growth and resources constraints: Issues of food, agriculture and development. Pop. Devel. Rev. 31, 237-258.

Alexandrov, V., Eitzinger, J., Cajic, V., Oberforster, M., 2002. Potential impact of climate change on selected agricultural crops in north-eastern Austria. Global Change Biol. 8, 372-389.

Alig, R.J., Adams, D.M., McCarl, B.A., 2002. Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets. Forest Ecol. Manage. 169, 3-14.

Alvarez, R., 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. Soil Use Manage. 21, 38-52.

Amelung, B., Viner, D., 2006. Mediterranean tourism: Exploring the future with the tourism climatic index. J. Sustain. Tourism (in press).

Amthor, J., 1998. Perspective on the relative insignificance of increasing atmospheric CO_2 concentration to crop yield. Field Crops Res. 58, 109-127.

Anderson, P.K., Cunningham, A.A., Patel, N.G., Morales, F.J., Epstein, P.R., Daszak, P., 2004. Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnology drivers. Trends Ecol. Evol. 19, 535-544.
André, J.-C., Déqué, M., Rogel, P., Planton, S., 2004. La vague de chaleur de l'été 2003 et sa prévision saisonnière. Geoscience 336, 491-503.
Antle, J.M., 1996. Methodological issues in assessing potential impacts of climate change on agriculture. Agric. Forest Meteorol. 80, 67-85.
Audsley, E., Pearn, K.R., Simota, C., Cojocaru, G., Koutsidou, E., Rounsevell, M.D.A., Trnka, M., Alexandrov, V., 2006. What can scenario modelling tell us about future European scale agricultural land use, and what not? Environ. Sci. Pol. 9, 148-168.
Baker, R.H.A., Sansford, C.E., Jarvis, C.H., Cannon, R.J.C., MacLeod, A., Walters, K.F.A., 2000. The role of climatic mapping in predicting the potential distribution of non-indigenous pests under current and future climates. Agric. Ecosyst. Environ. 82, 57-71.
Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M., Brown, V.K., Butterfield, J., Buse, A., Coulson, J.C., Farrar, J., Good, J.E.G., Harrington, R., Harley, S., Jones, T.H., Lindroth, R.L., Press, M.C., Symrnioudis, I., Watt, A.D., Whittaker, J.B., 2002. Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. Global Change Biol. 8, 1-16.
Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M., Kirk, G.J.D., 2005. Carbon losses from all soils across England and Wales 1978-2003. Nature 437, 245-248.
Beniston, M., 2004. The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. Geophys. Res. Let. 31, L02202.
Beniston, M., Diaz, H.F., 2004. The 2003 heat wave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland. Global Planet. Change 44, 73-81.
Benoit, M., le Torre, C.D., 2004: Changement climatique et observation à long terme en unités expérimentales ; évolution des pratiques agricoles et des réponses physiologiques des couverts végétaux. Journées MICCES 2004.
Berry, P.M., Rounsevell, M.D.A., Harrison, P.A., Audsley, E., 2006. Assessing the vulnerability of agricultural land use and species to climate change and the role of policy in facilitating adaptation. Environ. Sci. Pol. 9, 189-204.
Bindi, M., Ferrini, F., Miglietta, F., 1992. Climatic change and the shift in the cultivated area of olive trees. J. Agric. Mediter. 22, 41-44.
Bindi, M., Fibbi, L., Gozzini, B., Orlandini, S., Miglietta, F., 1996. Modeling the impact of future climate scenarios on yield and yield variability of grapevine. Clim. Res. 7, 213-224.
Bindi, M., Fibbi, L., Miglietta, F., 2001. Free air CO_2 enrichment (FACE) of grapevine (*Vitis vinifera* L.): II. Growth and quality of grape and wine in reponse to elevated CO_2 concentrations. Eur. J. Agron. 14, 145-155.
Bouma, J., Varallyay, G., Batjes, N.H., 1998. Principal land use changes anticipated in Europe. Agric. Ecosyst. Environ. 67, 103-119.
Bradshaw, B., Holly, D., Smit, B., 2004. Farm-level adaptation to climatic variability and change: crop diversification in the Canadian Prairies. Clim. Change 67, 119-141.
Buckland, S.M., Thompson, K., Hodgson, J.G., Grime, J.P., 2001, Grassland invasions: effects of manipulations of climate and management. J. Appl. Ecol. 38, 301-309.
Byrne, C., Jones M.B., 2002. Effects of elevated CO_2 and nitrogen fertilizer on biomass productivity, community structure and species diversity of a semi-natural grassland in Ireland. Proc. R. Irish Acad. 102B, 141-150.

Cannell, M.G.R., Thornley, J.H.M., 1998. N-poor ecosystems may respond more to elevated [CO_2] than N-rich ones in the long term. A model analysis of grassland. Global Change Biol. 4, 431-442.
Cannon, R.J.C., 1998. The implications of predicted climate change for insect pests in the UK, with emphasis on non-indigenous species. Global Change Biol. 4, 785-796.
Carter, T.R., Saarikko, R.A., Niemi, K.J., 1996. Assessing the risks and uncertainties of regional crop potential under a changing climate in Finland. Agric. Food Sci. Finland 3, 329-349.
Ceron, J.-P., Dubois, G., 2000. Tourisme et changement climatique. In: Impacts potentiels du changement climatique en France au XXIème siècle. 2d ed. Premier ministre, Ministère de l'aménagement du territoire et de l'environnement 1998. pp 104-111.
Chatskikh, D., Olesen, J.E., Berntsen, J., Regina, K., Yamulki, S., 2005. Simulation of effects of climate, soils and management on N_2O emission from grasslands. Biogeochemistry 76, 395-419.
Chen, C.C., McCarl, B.A., 2001. An investigation of the relationship between pesticide usage and climate change. Clim. Change 50, 475-487.
Chloupek, O., Hrstkova, P., Schweigert, P., 2004. Yield and its stability, crop diversity, adaptability and response to climate change, weather and fertilisation over 75 years in the Czech Republic in comparison to some European countries. Field Crops Res..85, 167-190.
Chmielewski, F.-M., Müller, A., Bruns, E., 2004. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000. Agric. Forest Meteorol. 121, 69-78.
Christensen, J.H., Christensen, O.B., 2002. Severe summertime flooding in Europe. Nature 421, 805-806.
Christensen, J.H., Christensen, O.B., 2006. A summary of PRUDENCE model projections of changes in European climate by the end of this century. Clim. Change (in press).
Ciais, Ph., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529-533.
Clifton-Brown, J.C., Stampfl, P.F., Jones, M.B., 2004. *Miscanthus* biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. Global Change Biol. 10, 509-518.
Coakley, S.M., Scherm, H., Chakraborty, S., 1999. Climate change and plant disease management. Annu. Rev. Phytopathol. 37, 399-426.
Cocu, N. et al., 2005. Geographical location, climate and land use influences on the phenology and numbers of the aphid, Myzus persicae, in Europe. J. Biogeography 32, 615-632.
Colebrook, E., Wall, R., 2004. Ectoparasites of livestock in Europe and the Mediterranean region. Vet. Parasitology 120, 251-274.
Darwin, R., 2004. Effects of greenhouse gas emissions on world agriculture, food consumption, and economic welfare. Clim. Change 66, 191-238.
Darwin, R., Kennedy, D., 2000. Economic effects of CO_2 fertilization of crops: transforming changes in yield into changes in supply. Environ. Model. Assess. 5, 157-168.
Davidsson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165-173.
Desjardins, R.L., Smith, W., Grant, B., Campbell, C., Riznek, R. 2005. Management strategies to sequester carbon in agricultural soils and to mitigate greenhouse gas emissions. Clim. Change 70, 283-297.

Drake, B.G., Gonzalez-Meier, M.A., Long, S.P., 1997. More efficient plants: a consequence of rising CO_2? Ann. Rev. Plant Physiol. Plant Mol. Biol. 48, 609-639.
Dueri, S., Calanca, P.L., Fuhrer, J., 2006. Climate change affects farm nitrogen loss - A Swiss case study with a dynamic farm model. Agric. Syst. (in press).
Duchene, E., Schneider, C., 2005. Grapevine and climatic changes: a glance at the situation in Alsace. Agron. Sustain. Devel. 25, 93-99.
Duckworth, J.C., Bunce, R.G.H., Malloch, A.J.C., 2000. Modelling the potential effects of climate change on calcareous grasslands in Atlantic Europe. J. Biogeography 27, 347-358.
Easterling, W.E., 1996. Adapting North American agriculture to climate change in review. Agric. Forest Meteorol. 80, 1-53.
Easterling, W.E., Apps, M., 2005. Assessing the consequences of climate change for food and forest resources: A view from the IPCC. Clim. Change 70, 165-189.
EEA, 2002. Environmental signals 2002. Benchmarking the millenium. Environmental assessment report No. 9. European Environmental Agency, Copenhagen, Denmark.
EEA, 2005. Annual European Community greenhouse gas inventory 1990-2003 and inventory report 2005. Submission to the UNFCCC Secretariat. EEA Technical report No 4/2005. European Environmental Agency, Copenhagen, Denmark.
Eisenreich, S.J. (Ed.), 2005. Climate change and the European Water Dimension. Report to the European Water Directors. European Commission-Joint Research Centre, Ispra, Italy. EUR 21553, 253 pp.
Elsasser, H., Burki, R., 2002. Climate change as a threat to tourism in the Alps. Climate Research 20, 253-257.
Estrela, T., Menéndez, M., Dimas, M., Marcuello, C., Rees, G., Cole, G., Weber, K., Grath, J., Leonard, J., Ovesen, N.B., Fehér, J., 2001. Sustainable water use in Europe. Part 3: Extreme hydrological events: floods and droughts. Environmental issue report No 21. European Environment Agency, Copenhagen.
Ewert, F., Rounsevell, M.D.A., Reginster, I., Metzger, M.J., Leemans, R., 2005. Future scenarios of European agricultural land use. I. Estimating changes in crop productivity. Agric. Ecosyst. Environ. 107, 101-116.
Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., Kammen, D.M., 2006. Ethanol can contribute to energy and environmental goals. Science 311, 506-508.
Fink, A.H., Brücher, T., Krüger, A., Leckebusch, G.C., Pinto, J.G., Ulbrich, U., 2004: The 2003 European summer heat waves and drought - Synoptic diagnosis and impact. Weather 59, 209-216.
Fischer, G., Shah, M., Tubiello, F.N., Van Velthuizen, H., 2005. Integrated assessment of global crop production. Phil. Trans. Roy. Acad. Sci. B 360, 2067-2083.
Flörke, M., Alcamo, J., 2005. European outlook on water use. Prepared for the European Environment Agency.
Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in European agricultural soils. Geoderma 122, 1-23.
Frich, P., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Tank, A.M.G.K., Peterson, T., 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. Climate Res. 19, 193-212.
Frolking, S., Roulet, N., Fuglestvedt, J., 2006. How Northern peatlands influence the Earth's radiative budget: Sustained methane emissions versus sustained carbon sequestration. Journal of Geophysical Research, Biogeosciences 11, G01008.
Fuhrer, J., 2003. Agroecosystem responses to combinations of elevated CO_2, ozone, and global climate change. Agriculture, Ecosyst. Environ. 97, 1-20.

Fuhrer, J., Beniston, M., Fischlin, A., Frei, C., Goyette, S., Jasper, K., Pfister, C., 2006. Climate risks and their impact on agriculture and forests in Switzerland. Clim. Change (in press).
Fuquay, J.W., 1989. Heat stress as it affects animal production. J. Animal Sci. 52, 164-174.
Galloway, J. N., Dentener, F. J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Anser, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vörösmarty, C.J., 2004. Nitrogen cycles: past, present, and future. Biogeochem. 70, 153-226.
Ghaffari, A., Cook, H.F., Lee, H.C., 2002. Climate change and winter wheat management: A modelling scenario for South-Eastern England. Clim. Change 55, 509-533.
Giorgi, F., Bi, X., Pal, J., 2004. Mean, interannual and trends in a regional climate change experiment over Europe. II: Climate Change scenarios (2071-2100). Clim. Dyn. 23, 839-858.
Gould, E.A., Higgs, S., Buckley, A., Gritsun, T.S., 2006. Potential arbovirus emergence and implications for the United Kingdom. Emerging Infect. Dis. 12, 549-555.
Grime, J.P., Brown, V.K., Thompson, K., Masters, G.J., Hillier, S.H., Clarke, I.P., Askew, A.P., Corker, D., Kielty, J.P., 2000. The response of two contrasting limestone grasslands to simulated climate change. Science 289, 762-765.
Hanson, C.E., Palutikof, J.P., Dlugolecki, A., Giannakopoulos, C., 2004. Bridging the gap between science and the stakeholder: the case of climate change research. Climate Research 13, 121-133.
Harrison, P.A., Butterfield, R.E., Orr, J.L., 2000. Modelling climate change impacts on wheat, potato and grapevine in Europe' In: Downing, T.E., Harrison, P.A., Butterfield, R.E., Lonsdale, K.G. (Eds.) Climate change, climatic variability and agriculture in Europe. Environmental Change Unit, University of Oxford, UK, pp. 367-390.
Helms, M., Büchele, B., Merkel, U., Ihringer, J., 2002. Statistical analysis of the flood situation and assessment of the impact of diking measures along the Elbe (Labe) river. J. Hydrol. 267, 94-114.
Hilden, M., Lethtonen, H. 2005. The practice and process of adaptation in Finnish agriculture. FINADAPT Working paper 5, Helsinki, Finnish Environment Institute Mimeographs 335.
Hogan, K.B., Hoffman, J.S., Thompson, A.M., 1991. Methane on the greenhouse agenda. Nature 354, 181-182.
Holden, N.M., Brereton, A.J., 2002. An assessment of the potential impact of climate change on grass yield in Ireland over the next 100 years. Irish J. Agric. Food Res. 41, 213-226.
Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric. Ecosyst. Environ. 103, 1-25.
Holman, I.P., Rounsevell, M.D.A., Shackley, S., Harrison, P.A., Nicholls, R.J., Berry, P.M., Audsley, E., 2005. A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: Part I Methodology. Clim. Change, 70, 9-41.
Hooijer, A., Klijn, F., Pedroli, G.B.M., van Os, A.G., 2004. Towards sustainable flood risk management in the Rhine and Meuse river basins: Synopsis of the findings of IRMA-SPONGE. River Res. Appl. 20, 343-357.
Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., 2001. Climate change 2001: The scientific basis. Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.
IPCC, 1997. Greenhouse Gas Inventories. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.
Johansson, M., Christensen, T.R., Akerman, H.J., Callaghan, T.V., 2006. What determines the current presence or absence of permafrost in the Torneträsk region, a sub-arctic landscape in Northern Sweden. Ambio 35, 190-197.
Jones, G.V., Davis, R., 2000. Climate influences on grapewine phenology, grape composition, and wine production and quality for Bordeaux, France. Am. J. Enol. Viticult. 51, 249-261.

Jones, G.V., White, M.A., Cooper, O.R., Storchmann, K., 2005. Climate change and global wine quality. Clim. Change 73, 319-343.
Jones, P.D., Moberg, A., 2003. Hemispheric and large scale surface air temperature variations: an extensive revision and an update to 2001. J. Clim. 16, 206-223.
Jones, P.D., Lister, D.H., Jaggard, K.W., Pidgeon, J.D., 2003. Future climate impact on the productivity of sugar beet (*Beta vulgaris* L.) in Europe. Clim. Change 58, 93-108.
Kaiser, H.M., Riha, S.J., Wilks, D.S., Rossiter, D.G., Sampath, R., 1993. A farm-level analysis of economic and agronomic impacts of gradual climate warming. Am. J. Agric. Econ. 75, 387-398.
Kammann, C., Grünhage, L., Grüters, U., Janze, S., Jäger, H.-J., 2005. Response of aboveground grassland biomass to moderate long-term CO_2 enrichment. Basic Appl. Ecol. 6, 351-365.
Kenny, G.J., Harrison, P.A., Olesen, J.E., Parry, M.L., 1993, The effects of climate change on land suitability of grain maize, winter wheat and cauliflower in Europe. Eur. J. Agron. 2, 325-238.
Kimball, B.A., Kobayahsi, K., Bindi, M., 2002. Responses of agricultural crops to free-air CO_2 enrichment. Adv. Agron. 77, 293-368.
Kjellström, E., 2004. Recent and future signatures of climate change in Europe. Ambio 33, 193-198.
Klein Tank, A.M.G., 2004. Changing temperature and Precipitation extremes in Europe's climate of the 20th Century. Utrecht, University of Utrecht.
Klein Tank, A.M.G., Können, G.P., 2003. Trends in indices of daily temperature and precipitation extremes in Europe. J. Clim. 16, 3665-3680.
Klein Tank, A.M.G. et al., 2002. Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. Int. J. Clim. 22, 1441-1453.
Klinedienst, P.L., Wilhite, D.A., Hahn, G.L., Hubbard, K.G., 1993. The potential effects of climate change on summer season dairy cattle milk production and reproduction. Clim. Change 23, 21-36.
Lallana, C., Kriner, W., Estrela, R., Nixon, S., Leonard, J., Berland, J.J., 2001. Sustainable Water Use in Europe, Part 2: Demand Management. Environmental Issues Report No. 19. European Environmental Agency, Copenhagen.
Lehner, B., Döll, P., Alcamo, J., Henrichs, H., Kaspar, F., 2006, Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis, Clim. Change 75, 273-299.
Leishman, M.R., Masters, G.J., Clarke, I.P., Brown, V.K., 2000. Seed bank dynamics: the role of fungal pathogens and climate change. Func. Ecol. 14, 293-299.
Lelieveld, J., Crutzen, P.J., Denener, F.J., 1998. Changing concentration, lifetime and climate forcing of atmospheric methane. Tellus 50B, 128-150.
Lobell, D.B., Asner, G.P., 2003. Climate and management contributions to recent trends in U.S. agricultural yields. Science 299, 1032.
Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nösberger, J., Ort, D.R., 2006. Food for thought: Lower-than-expected crop yield stimulation with rising CO_2 concentrations. Science 312, 1918-1921.
Lüscher, A., Daepp, M., Blum, H., Hartwig, U.E., Nösberger, J., 2004. Fertile temperate grassland under elevated atmospheric CO_2 - role of feed-back mechanisms and availability of growth resources. Eur. J. Agron. 21, 379-398.
MacDonald, G.M., Beilman, D.W., Kremenetski, K.V., Sheng, Y., Smith, L.C., Velichko, A.A., 2006. Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. Science 314, 285-288.
Mader, T.L., Davis, M.S., 2004: Effect of management strategies on reducing heat stress of feedlot cattle: feed and water intake. J. Animal Sci. 82, 3077-3087.
Mader, T.L., Holt, S.M., Hahn, G.L., Daivs, M.S., Spiers, D.E., 2002. Feeding strategies for

managing heat load in feedlot cattle. J. Animal Sci. 80, 2373-2382.
Maracchi, G., Sirotenko, O., and Bindi, M., 2005. Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe. Clim. Change 70, 117-135.
Marsh, J., 2005. The implications of Common Agricultural Policy reform for farmers in Europe. Farm Pol. J. 2 (2), 1-11.
Meehl, G.A., Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st Century. Science 305, 994-997.
Mellor, P.S., Wittmann, E.J., 2002. Bluetongue virus in the Mediterranean Basin 1998-2001. Vet. J. 164, 20-37.
Mendelsohn, R., Dinar, A., 1999. Climate change, agriculture, and developing countries: Does adaptation matter? World Bank Obs. 14, 277-293.
Menzel, A., 2003. Plant phenological anomalies in Germany and their relation to air temperature and NAO. Clim. Change 57, 243.
Merbach, W., Augustin, J., Kalettka, T., Jacob, H.J., 1996. Nitrous oxide and methane emissions from riparian areas of ponded depressions of Northeast Germany. Angew. Bot. 70, 134-136.
Metzger, M.J., Rounsevell, M.D.A., Acosta-Michlik, L., Leemans, R., Schröter, D., 2006. The vulnerability of ecosystem services to land use change. Agric. Ecosyst. Environ. 114, 69–85.
Minguez, M.I., Ruiz-Ramos, M., Díaz-Ambrona, C.H., Quemada, M., Sau, F., 2006. First-order impacts on winter and summer crops assessed with various high-resolution climate models in the Iberian peninsula. Clim. Change (in press).
Monteny, G.-J., Bannink, A., Chadwick, D., 2006. Greenhouse gas abatement strategies for animal husbandry. Agric. Ecosyst. Environ. 112, 163-170.
Moriondo, M., Bindi, M., Giannakopoulos, C., Corte Real, J., 2006. Impact of changes in climate extremes on winter and summer agricultural crops at the Mediterranean scale. Clim. Res. (in press).
Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., van Cleemput, O., 1998. Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutr. Cycl. Agroecosys. 52, 225-248.
Mosier A.R., Halvorsen A.D., Peterson G.A., Robertson G.P., Sherrod L.A., 2005. Measurement of net global warming potential in three agroecosystems. Nutr. Cycl. Agroecosyst. 72, 67-76.
Moss, A.R., Jouany, J.P., Newbold, J., 2000. Methane production by ruminants: Its contribution to global warming. Ann. Zootech. 49, 231-253.
Moss, B., Mckee, D., Atkinson, D., Collings, S.E., Eaton, J.W., Gill, A.B., Harvey, I., Hatton, K., Heyes, T., Wilson, D., 2003. How important is climate? Effects of warming, nutrient addition and fish on phytoplankton in shallow lake microcosms. J. Appl. Ecol. 40, 782-792.
Nixon, S., Trent, Z., Marcuello, C, Lallana, C., 2003. Europe's water: An indicator-based assessment. Topic report 1/2003. European Environment Agency, Copenhagen.
OECD, 2004. Analysis of the 2003 CAP reform. OECD publications, Paris.
Oenema, O., Wrage, N., Velthof, G.L., Groeningen, J.W. van, Dolfing, J., Kuikman, P.J., 2005. Trends in global nitrous oxide emissions from animal production systems. Nutr. Cycl. Agroecosyst. 72, 51-65.
Ogle, S.M., Breidt, F.J., Paustian K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochem. 72, 87–121.
Olesen, J.E., Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. Eur. J. Agron. 16, 239-262.
Olesen, J.E., Bindi, M., 2004. Agricultural impacts and adaptations to climate change in Europe. Farm Pol. J. 1(3), 36-46.

Olesen, J.E., Carter, T.R., Diaz-Ambrona, C.H., Fronzek, S., Heidmann, T., Hickler, T., Holt, T., Minguez, M.I., Morales, P., Palutikov, J., Quemada, M., Ruiz-Ramos, M., Rubæk, G., Sau, F., Smith, B., Sykes, M., 2006a. Uncertainties in projected impacts of climate change on European agriculture and ecosystems based on scenarios from regional climate models. Clim. Change (in press).
Olesen, J.E., Jensen, T., Petersen, J., 2000. Sensitivity of field-scale winter wheat production in Denmark to climate variability and climate change. Clim. Res. 15, 221-238.
Olesen, J.E., Schelde, K., Weiske, A., Weisbjerg, M.R., Asman, W.A.H., Djurhuus, J., 2006b. Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agric. Ecosyst. Environ. 112, 207-220.
Pal, J.S., Giorgi, F., Bi, X.Q., 2004. Consistency of recent European summer precipitation trends and extremes with future regional climate projections. Geophys. Res. Let. 31, L13202.
Parry, M.L. (ed.), 2000. Assessment of potential effects and adaptations for climate change in Europe: The Europe ACACIA project. Jackson Environment Institute, University of East Anglia, Norwich, United Kingdom.
Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environ. Change 14, 53-67.
Parry, M.L., Rosenzweig, C., Livermore, M., 2005. Climate change, global food supply and risk of hunger. Phil. Trans. R. Soc. B 360, 2125-2138.
Peyrache-Gadeau, V., Fleury, P., 2005. Agriculture as an agent in building local identities: an alternative approach to urbanization of rural areas as exemplified in the Alpine corridor. Journal of Alpine Research 93, 21-32.
Porter, J.R., Gawith, M., 1999. Climatic variability and development of wheat: a review. Eur. J. Agron. 10, 23-36.
Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Phil. Trans. R. Soc. B 360, 2021-2035.
Porter, J..R., Leigh,R.A., Semenov, M.A., Miglietta, F., 1995. Modelling the effects of climatic change and genetic modification on nitrogen use by wheat. Eur. J. Agron. 4, 419-429.
Ragab, R., Prudhomme, C., 2002. Climate change and water resources management in arid and semi-arid regions: Prospective and challenges for the 21st century. Biosystems Engineering 81, 3-34.
Reilly, J., Schimmelpfennig, D., 1999. Agricultural impact assessment, vulnerability, and the scope for adaptation. Clim. Change 43, 745-788.
Rivington, M., Matthews, K.B., Bellocchi, G., Buchan, K., Stöckle, C.O., Donatelli, M., 2006. An integrated modelling approach to conduct multi-factorial analyses on the impacts of climate change on whole-farm systems. Environ. Model. Software 22, 202-210.
RMS, 2003. Central Europe flooding, August 2002. Event report. Risk Management Solutions, Inc.
Robertson, G.P., Paul, E.A., Harwood, R.R., 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. Science 289, 1922-1925.
Rochette, P., Belanger, G., Castonguay, Y., Bootsma, A., Mongrain, D., 2004. Climate change and winter damage to fruit trees in eastern Canada. Can. J. Plant Sci. 84, 1113-1125.
Rounsevell, M.D.A., Ewert, F., Reginster, I., Leemans, R., Carter, T.R., 2005. Future scenarios of European agricultural land use. II. Projecting changes in cropland and grassland. Agric. Ecosyst. Environ. 107, 117-135.
Rounsevell, M.D.A., Reginster, I., Araújo, M.B., Carter, T.R., Dendoncker, N., Ewert, F., House, J.I., Kankaanpää, S., Leemans, R., Metzger, M.J., Schmit, C., Smith, P., Tuck, G., 2006. A

coherent set of future land use change scenarios for Europe. Agric. Ecosyst. Environ. 114, 57-68.
Ruddiman, W.F., 2003. The anthropogenic greenhouse era began thousands of years ago. Clim. Change 61, 261-293.
Ruosteenoja, K., Carter, T.R., Jylhä, K., Tuomenvirta, H., 2003. Future climate in world regions: an intercomparison of model-based projections for the new IPCC emissions scenarios. Finnish Environment Institute, Helsinki, Finland.
Rustad, L.E., Campbell, J.L, Marion, G.M., Borby, R.J., Mitchell, M.J., Hartley, A.E., Cornelissen, J.H.C., Gurevitch, J., 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. Oecologica 126, 543-562.
Salinari, F., Giosue, S., Tubiello, F.N., Rettori, A., Rossi, V., Spanna, F., Rosenzweig, C., Gullino, M.L., 2006. Downy mildew (*Plasmopara viticola*) epidemics on grapevine under climate change. Global Change Biol. 12, 1299-1307.
Santos, F.D., Forbes, K., Moita, R. (eds.) 2002. Climate change in Portugal: Scenarios, Impacts and Adaptation Measures. SIAM project report, Gradiva, Lisbon, Portugal, 456 pp.
Schär, C., Jendritzky, G., 2004. Climate change: Hot news from summer 2003. Nature 432, 559-560.
Schär, C., Vidale, P.L., Lüthi, D., Frei, C., Häberli, C., Liniger, M.A., Appenzeller, C., 2004. The role of increasing temperature variability in European summer heatwaves. Nature 427, 332-336.
Schröter, D., Cramer, W., Leemans, R., Prentice, I.C., Araújo, M.B., Arnell, N.W., Bondeau, A., Bugmann, H., Carter, T.R., Gracia, C.A., de la Vega-Leinert, A.C., Erhard, M., Ewert, F., Glendining, M., House, J.I., Kankaapää, S., Klein, R.J.T., Lavorel, S., Lindner, M., Metzger, M.J., Meyer, J., Mitchell, T.D., Reginster, I., Rounsevell, M., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S., Zierl, B., 2005. Ecosystem service supply and vulnerability to global change in Europe. Science 310, 1333-1337.
Schils, R.L.M., Verhagen, A., Aarts, H.F.M., Kuikman, P.J., Sebek, L.B.J., 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. Global Change Biol. 12, 382-391.
Schultz, B., 2006. Flood management under rapid urbinisation and industrialisation in flood-prone areas: A need for serious consideration. Irrigation and Drainage 55, S3-S8.
Sims, R.E.H., Hastings, A., Schlamadinger, B., Taylor, G., Smith, P., 2006. Energy crops: current status and future prospects. Global Change Biol. 12, 2054-2076.
Sinclair, T.R., Muchow, R.C., 2001. Systems analysis of plant traits to increase grain yield on limited water supplies. Agron. J. 93, 263-270.
Sirotenko, O.D., Abashina, H.V., Pavlova, V.N., 1997. Sensitivity of the Russian agriculture to changes in climate, CO_2 and tropospheric ozone concentrations and soil fertility. Clim. Change 36, 217-232.
Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Global Change Biol. 10, 155-160.
Smith, J.B., Lenhart, S.S., 1996. Climate change adaptation policy options. Clim. Res. 6, 193-201.
Smith, K.A., McTaggart, I.P., Tsuruta, H., 1997. Emissions of N_2O and NO associated with nitrogen fertilization in intensive agriculture, and the potential for mitigation. Soil Use Manage. 13, 296-304.
Smith, P., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K., 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. Glob. Chang. Biol. 6, 525-539.

Smith, P., Goulding, K.W., Smith, K.A., Powlson, D.S., Smith, J.U., Falloon, P.D., Coleman, K., 2001. Enhancing the carbon sink in European agricultural soils: Including trace gas fluxes in estimates of carbon mitigation potential. Nutr. Cycl. Agroecosyst. 60, 237–252.
Smith, J., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I., Ewert, F., 2006. Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. Global Change Biol. 11, 2141-2152.
Sommer, S.G., Olesen, J.E., 2000. Modelling ammonia volatilization from animal slurry applied to cereals. Atmos. Environ. 34, 2361-2372.
Sommer, S.G., Géneremont, S., Cellier, P., Hutchings, N.J., Olesen, J.E., Morvan, T., 2003. Processes controlling ammonia emission from livestock slurry in the field. Eur. J. Agron. 19, 465-486.
Sommer, S.G., Petersen, S.O., Møller, H.B., 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutr. Cycl. Agroecosyst. 69, 143-154.
Stern, N., 2006. The economics of climate change. The Stern Review. Cambridge University Press, UK.
Strack, M., Waller, M.F., Waddington, J.M., 2006. Sedge succession and peatland methane dynamics: A potential feedback to climate change. Ecosystems 9, 278-287.
Ström, L., Mastepanov, M., Christensen, T.R., 2005. Species-specific effects of vascular plants on carbon turnover and methane emissions from wetlands. Biogeochemistry 75, 65-82.
Tait, J., 2001. Science, governance and multifunctionality of European agriculture. Outlook Agric. 30, 91-95.
Tavakkoli, A.R., Oweis, T.Y., 2006. The role of supplemental irrigation and nitrogen in producing bread wheat in the highlands of Iran. Agric. Water Manage. 65, 225-236.
Thornley, J.H.M., Cannell, M.G.R., 1997. Temperate grassland responses to climate change: an analysis using the Hurley pasture model. Ann. Bot. 80, 205-221.
Topp, C.F.E., Doyle, C.J., 1996. Simulating the impact of global warming on milk and forage production in Scotland: 2. The effects on milk yields and grazing management of dairy herds. Agric. Syst. 52, 243-270.
Trettin, C.C., Laiho, R., Minkkinen, K., Laine, J., 2006. Influence of climate change factors on carbon dynamics of northern forested peatlands. Canadian Journal of Soil Science 86, 269-280.
Trnka, M., Dubrovski, M., Semerádová, D., Zalud, Z., 2004. Projections of uncertainties in climate change scenarios into expected winter wheat yields. Theor. Appl. Meteorol. 77, 229-249.
Tubiello F.N., Donatelli, M., Rosenzweig, C., Stockle, C.O., 2000. Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations. Eur. J. Agron. 13, 179-189.
Tuck, G., Glendining, M.J., Smith, P., House, J.I., Wattenbach, M., 2006. The potential distribution of bioenergy crops in Europe under present and future climate. Biomass Bioener. 30, 83-197.
Turnpenny, J.R., Parsons, D.J., Armstrong, A.C., Clark, J.A., Cooper, K., Matthews, A.M., 2001. Integrated models of livestock systems for climate change studies. 2. Intensive systems. Global Change Biol. 7, 163-170.
van der Ploeg, R.R., Schweigert, P., 2001. Elbe river flood peaks and postwar agricultural land use in East Germany. Naturwissenschaft 88, 522-525.
van der Vaart, J.H.P., 2005. Towards a new rural landscape: consequences of non-agricultural re-use of redundant farm buildings in Friesland. Landscape and Urban Planning 70, 143-152.
van Ittersum, M.K., Howden, S.M., Asseng, S., 2003. Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in CO_2, temperature and precipitation. Agric. Ecosyst. Environ. 97, 255-273.

van Meijl, H., van Rheenen, T., Tabeau, A., Eickhout, B., 2006. The impact of different policy environments on agricultural land use in Europe. Agric. Ecosyst. Environ. 114, 21-38.
Viner, D., 2006. Tourism and its interactions with climate change. Journal of Sustainable Tourism 14, 317-322.
Wadsworth, R., Swetnam, R., 1988. Modelling the impact of climate warming at the landscape scale: will bench terraces become economically and ecologically viable structures under changed climates? Agric. Ecosyst. Environ. 68, 27-39.
Weiske, A., Vabitsch, A., Olesen, J.E., Schelde, K., Michel, J., Friedrich, R., Kaltschmitt, M., 2006. Mitigation of greenhouse gas emissions in European conventional and organic dairy farming. Agric. Ecosyst. Environ. 112, 221-232.
Wheeler, T.R., Crauford, P.Q., Ellis, R.H., Porter, J.R., Vara Prasad, P.V., 2000. Temperature variability and the yield of annual crops. Agric. Ecosyst. Environ. 82, 159-167.
Wittmann, E.J., Baylis, M., 2000. Climate change: Effects on Culicoides-transmitted viruses and implications for the UK. Vet. J. 160, 107-117.
Wickland, K.P., Striegl, R.G., Neff, J.C., Sachs, T., 2006. Effects of permafrost melting on CO_2 and CH_4 exchange of a poorly drained black spruce lowland. Journal of Geophysical Research, Biogeoosciences 11, G02011.
Wolf, J., van Oijen, M., 2003. Model simulation of effects of changes in climate and atmospheric CO_2 and O_3 on tuber yield potential of potato (cv. Bintje) in the European Union. Agric. Ecosyst. Environ. 94, 141-57.
Zangl, G., 2004. Numerical simulations of the 12-13 August 2002 flooding event in eastern Germany. Quart. J. R. Met. Soc. 130, 1921-1940.
Ziska, L.H., Bunce, J.A., 1997. Influence of increasing carbon dioxide concentration on the photosynthetic and growth stimulation of selected C_4 crops and weeds. Photosyn. Res. 54, 199-208.
Zhou, L.M. et al. 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. J. Geophys. Res. Atmos. 106, 20069-20083.
Zhuang, Q.L., Melillo, J.M., Sarofim, M.C., Kicklighter, D.W., McGuire, A.D., Felzer, B.S., Sokolov, A., Prinn, R.G., Steudler, P.A., Hu, S.M., 2006. CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. Geophysical Research Letters 33, L17403.