

Review

Consequences of climate change for European agricultural productivity, land use and policy

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Abstract

This paper reviews the knowledge on effects of climate change on agricultural productivity in Europe and the consequences for policy and research. Warming is expected to lead to a northward expansion of suitable cropping areas and a reduction of the growing period of determinate crops (e.g. cereals), but an increase for indeterminate crops (e.g. root crops). Increasing atmospheric CO₂ concentrations will directly enhance plant productivity and also increase resource use efficiencies.

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 the turnover 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.

Policy will have to support the adaptation of European agriculture to climate change by encouraging the flexibility of land use, crop production, farming systems etc. In doing so, it is necessary to consider the multifunctional role of agriculture, and to strike a variable balance between economic, environmental and social functions in different European regions. Policy will also need to be concerned with agricultural strategies to mitigate climate change through a reduction in emissions of methane and nitrous oxide, an increase in carbon sequestration in agricultural soils and the growing of energy crops to substitute fossil energy use. The policies to support adaptation and mitigation to climate change will need to be linked closely to the development of agri-environmental schemes in the European Union Common Agricultural Policy.

Research will have further to deal with the effect on secondary factors of agricultural production, on the quality of crop and animal production, of changes in frequency of isolated and extreme weather events on agricultural production, and the interaction with the surrounding natural ecosystems. There is also a need to study combined effects of adaptation and mitigation strategies, and include assessments of the consequences on current efforts in

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agricultural policy to develop a sustainable agriculture that also preserves environmental and social values in the rural society. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Agriculture is situated at the interface between ecosystems and society. As such agriculture is affected by the changes in the global environmental conditions, but agriculture also contributes to about 20% of the emissions of greenhouse gases, notably methane and nitrous oxide (Rosenzweig and Hillel, 2000). The agricultural ecosystems vary from highly intensive farming systems such as the arable cropping systems of western Europe to the low-input farming systems such as subsistence farming in sub-Saharan Africa. The highest emissions of greenhouse gases from agriculture are generally associated with the intensive farming systems (IPCC, 1997), whereas some of the low input farming systems currently located in marginal areas may be most severely affected by climate change (Reilly and Schimmelpfennig, 1999; Kates, 2000).

The overall driving force in agriculture is the globally increasing demand for food and fibre. This is primarily caused by a growing world population with a high demand for food production and a wealthier world population with a higher proportion of meat in the diet (Evans, 1998). The result is that agriculture globally exerts increasing pressure on the land and water resources of the earth, which often results in land degradation, e.g. soil erosion, salinisation and pollution (Kirchmann and Thorvaldsson, 2000).

Climate change is expected to affect agriculture very differently in different parts of the world (Parry et al., 1999). 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; Rabbinge and van Diepen, 2000). These

differences are expected also to greatly influence the responsiveness to climatic change (Parry, 2000).

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 (Beniston and Tol, 1998). Results of GCM model simulations indicate that large climatic changes may occur over the European continent as a result of the likely increase in atmospheric concentrations of greenhouse gases caused by anthropogenic emissions. The results of an analysis of a number of GCM simulations indicate that annual temperatures over Europe warm at a rate of between 0.1 and 0.4 °C decade⁻¹ (Parry, 2000). The greatest increases are expected over southern Europe and north-east Europe. The general pattern of future changes in annual precipitation over Europe is for widespread increases in northern Europe (between +1 and +2 percent decade⁻¹), rather small decreases over southern Europe (maximum -1 percent decade⁻¹) and small changes in central Europe.

The aim of this paper is to review the current knowledge on the impact of climate change on agriculture in Europe and to put this into the context of current agricultural policy. The paper discusses the possible effects of climate change on European agricultural policy as well as the interaction between agriculture and other important sectors of European society.

2. European agriculture

Europe is one of the world's largest and most productive suppliers of food and fibre (Table 1). The 15 countries of the European Union (EU) thus alone accounted for 10% of the global cereal production and 16% of global meat production in 1998.

Table 1

Population, land area, agricultural area and annual production in the EU, the EU+12 and in Europe in per cent of total world sums

	World	EU (%)	EU+12 (%)	Europe (%)
Population (million)	5666	13	17	26
Land area (Mha)	13048	2	3	17
Agricultural area (Mha)	4938	3	4	10
Cereal production (Gt)	2081	10	14	19
Pulses production (Gt)	56	11	12	17
Oil crop production (Gt oil)	103	7	9	12
Root and tuber production (Gt)	648	7	12	21
Fruit production (Gt)	433	12	14	17
Vegetable production (Gt)	626	9	11	15
Fibre crop production (Gt)	23	3	3	4
Meat production (Gt)	223	16	20	24
Milk production (Gt)	562	22	27	39

Population data are based on FAO statistics from year 1995, and land use and production data are based on FAO statistics from 1998. The EU currently covers 15 countries, and 13 countries have applied for EU membership. The EU+12 covers current EU member countries plus countries that have applied for membership, excluding Turkey.

Agriculture in the EU accounts for only 2% of the total GDP, but accounts for 5.6% of total employment. The vulnerability of the overall economy to changes that affect agriculture is therefore low, but locally effects may be large. Throughout Europe dairy and meat production are major activities, which in combination with intensive arable farming systems result in high agricultural outputs in both EU and in Europe as a whole (Table 1). Agricultural land use in the different regions in Europe is shown in Table 2.

Europe can be divided into a number of major agricultural regions determined by both environmental and socio-economic factors (Fig. 1). Regions 1 to 5 in Fig. 1 are mainly characterised by market-oriented agriculture, which has been heavily influenced by the EU Common Agricultural Policy (CAP). Agriculture in the northern region 1 is limited by climatic and soil conditions and only a small percentage of the land is cultivated (Table 2). Agriculture in large parts of region 2 is dominated by the wet conditions along the Atlantic coasts, and grasslands dominate this area. More intensive arable and livestock farming is seen in region 3, which has small-scale, mixed or large-scale intensive farming systems. In the mountainous region 5 both market-oriented agriculture and transitional forms from extensive mixed farms to market-oriented farming occur.

Region 4 is characterised by the drier and warmer Mediterranean climate, which has led to a diverse pattern of agriculture. A market-oriented type of agriculture with mainly crop cultivation, including fruit trees, olive and grapes, predominates (Table 2). Alternatively, in this region considerable areas of the traditional small-scale type of agriculture still occur (Kostrowicki, 1991).

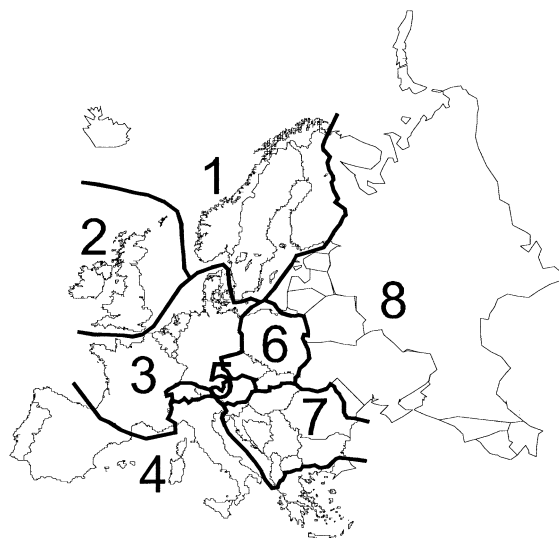


Fig. 1. Major agricultural regions in Europe (see Table 2 for region names and characteristics).

Table 2
Land use and population in different regions of Europe based on FAO statistics from 1998

Region	Agricultural area		Percent of agricultural area				Population		
	Mill. ha	% of land	Arable	Cereals	Permanent crops ^a	Permanent pasture	Irrigated	Total (mill.)	Rural (%)
1. Nordic	6.6	6	89	42	0	11	5	19	25
2. British Isles	21.9	70	35	17	0	65	0	62	13
3. Western	53.4	52	64	34	3	33	7	171	17
4. Mediterranean	58.1	56	47	21	16	37	14	118	33
5. Alpine	5.0	40	36	20	2	62	1	15	37
6. North eastern	22.7	57	75	46	3	22	1	49	36
7. South eastern	44.0	57	61	36	4	34	10	72	42
8. Eastern	286.9	16	61	19	1	37	3	173	27

Population statistics are from 1995.

^a Permanent crops are crops that occupy land for many years, e.g. flowering shrubs, fruit trees, nut trees and vines.

Table 3

Development in wheat area and wheat yield (16% moisture content) in main European regions

Region	Wheat area (1000 ha)			Wheat yield (Mg ha ⁻¹)		
	1975–1979	1985–1989	1995–1999	1975–1979	1985–1989	1995–1999
1. Nordic	495 ^a	477 ^a	509 ^a	3.7 ^a	4.4 ^b	5.2 ^c
2. British Isles	1243 ^a	2038 ^b	2034 ^b	4.7 ^a	6.5 ^b	7.8 ^b
3. Western	6870 ^a	8005 ^b	8724 ^c	4.4 ^a	6.0 ^b	7.1 ^c
4. Mediterranean	7392 ^a	6430 ^b	5597 ^c	2.1 ^a	2.6 ^b	2.7 ^b
5. Alpine	369 ^a	403 ^b	356 ^a	3.9 ^a	5.0 ^b	5.4 ^c
6. North eastern	3001 ^a	3304 ^b	3367 ^b	3.3 ^a	4.1 ^{ab}	3.7 ^b
7. South eastern	6301 ^a	6438 ^a	5215 ^b	3.1 ^a	3.7 ^b	3.1 ^a
8. Eastern	—	—	32710	—	—	1.6

Data is based on FAO statistics. Numbers with different letters within a row in each category are significantly different at the 95% confidence level.

Regions 6–7 in Fig. 1 had three types of agriculture: traditional, market-oriented and socialised agriculture. The extent of the latter category has been rapidly diminishing since the late 1980s, leading to a type of agriculture that resembles western Europe. Root crops and cereals are important in this region. Yields are, however, low due to low production intensity. A large proportion of the population in these countries lives in rural areas (Table 2). Region 8 is the European part of the former USSR, which used to be dominated by large-scale socialised agriculture, but which is now slowly adapting to a more quality-oriented agriculture (Bouma et al., 1998).

The proportion of the population that lives in rural areas is highest in the Alpine and Mediterranean countries and in the former socialised countries of central and eastern Europe (Table 2). More than 40% of the population in south-eastern Europe thus live in rural areas, which makes this population highly dependent on agriculture.

2.1. Trends in European agriculture

The trends in European agriculture are dominated by the CAP of the EU. The CAP reform of 1992 reduced intervention prices by one third and substituted this by area payments, including set-aside schemes. This process of reducing and transforming subsidies is continued in the new CAP reform, which is part of the Agenda 2000 reform (CEC, 1999). There is need for further reform to

facilitate the accession of eastern European countries into the EU.

The trends in European agriculture can be illustrated by the development of wheat area and yield over the past 25 years (Table 3). Yields have increased rapidly by about 0.15 Mg ha⁻¹ yr⁻¹ in the northwestern part of Europe (regions 2 and 3). Yields in the Nordic and Alpine regions have increased by only half this rate, and there has been virtually no change in yields in the Mediterranean region (Supit, 1997). This has led to a reduction in wheat area in the Mediterranean region and an increase in northwestern Europe. The wheat yield in the former socialised countries of central and eastern Europe (regions 6 and 7) have declined following the change to democracy and liberalised economies in the late 1980s.

2.2. Climatic constraints to European agriculture

Biological systems are based primarily on photosynthesis, and are thus dependent on incoming radiation. However, the potential for production set by the radiation is greatly modified by temperature and rainfall. The main effect of temperature is to control the duration of the period when growth is possible in each year (Rötter and van de Geijn, 1999). Also other processes linked with the accumulation of dry matter (leaf area expansion, photosynthesis, respiration etc.) are directly affected by temperature. Rainfall and soil water availability may affect the duration of growth

through effects on leaf area duration and the photosynthetic efficiency through stomatal closure.

In northern countries the length of the growing season, late spring and early autumn frosts and solar radiation availability are typical climatic constraints. In these environments the duration of the growing season (frost or snow-free period) limits the productivity of crops. For example in Germany the growing season is 1–3 months longer than in Scandinavian countries (Mela, 1996). The short growing season is the main cause of the lower wheat yields in the Nordic countries (Table 3). Moreover, night frosts in late spring or early autumn increase the agricultural risk in these environments.

The wet conditions along the Atlantic coast and in the mountainous regions causing cold and rainy summers cause yield and quality losses in many arable crops. These wet conditions also affect soil workability and reduce the number of machinery work-days (Brignall and Rounsevell, 1995). This is the main reason for the small area put down to cereals in the British Isles and Alpine countries compared with other regions (Table 2). Permanent pastures dominate in these areas.

In Mediterranean countries cereal yields are limited by water availability, heat stress and the short duration of the grain-filling period. Permanent crops (olive, grapevine, fruit trees etc.) are therefore more important in this region. These crops are affected by extreme weather events (such as hail and storms) which can reduce or completely destroy yield. Irrigation is important for crop production in many Mediterranean countries due to high evapotranspiration and restricted rainfall.

The continental climate of eastern Europe (from central Poland and eastwards) causing drier conditions and greater amplitude of the annual temperature cycle limits the range of crops that can be grown. The most productive regions in Europe in terms of climate and soils are located in the great European plain stretching from South-east England through France, Benelux and Germany into Poland. There are additional lowland regions, e.g. the Hungarian plains, where equally favourable conditions prevail. However, the

largest areas with predominantly suitable soils are found in Ukraine, Belarus and Russia (Rabbinge and van Diepen, 2000), which is also revealed in the large wheat growing area of the eastern European region (Table 3).

The yields in eastern Europe have been restricted considerably by the agricultural policies and the socio-economic conditions in these countries. This can be demonstrated by the study performed by Rabbinge and van Diepen (2000), who compared simulated water limited wheat yields with the observed national wheat yields for all of Europe. Fig. 2 shows that the simulated yields are in fairly good agreement with the observed yields for countries of EU and western Europe, whereas simulated yields for the former socialised countries are considerably higher than observed yields. In particular the simulated yield for Belarus is 9.5 Mg ha^{-1} compared with an observed yield of only 2.3 Mg ha^{-1} .

Fig. 2 shows some deviations between three different simulation studies for EU countries. Both van Lanen et al. (1992) and Rabbinge and van Diepen (2000) used the WOFOST model, but the latter study used a more detailed soil and climate database, and these results are therefore probably more credible.

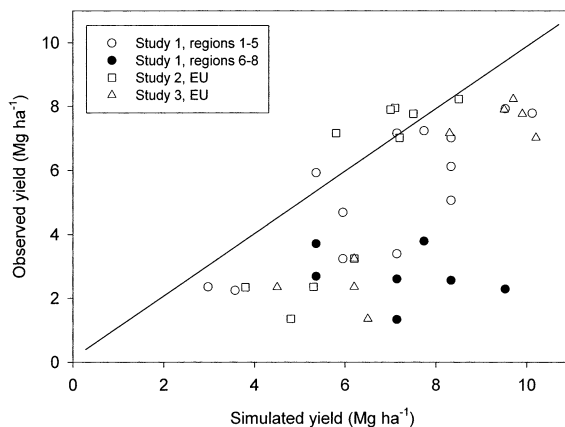


Fig. 2. Observed versus simulated regional or national wheat grain yields (16% moisture content) for three studies; (1) Rabbinge and van Diepen (2000), (2) van Lanen et al. (1992), (3) Harrison et al. (2000a).

3. Biophysical response to climate change

Biophysical processes of agroecosystems are strongly affected by environmental conditions. The projected increase in greenhouse gases will affect agroecosystems either directly (e.g. response to CO₂ and tropospheric ozone) or indirectly via effects on climate (e.g. temperature and rainfall). The exact responses depend on the sensitivity of the particular ecosystem and on the relative changes in the controlling factors.

3.1. CO₂ effects on system productivity

Plant photosynthesis has long been known to respond to atmospheric CO₂ concentration (Dahlman, 1993). However, this response depends on the photosynthetic pathway of the plants. The response is thus much smaller in C₄-plants (tropical plants including maize) compared with C₃-plants (Allen, 1990).

The second primary effect of CO₂ enrichment on plants is to reduce stomatal aperture and stomatal density, which causes a reduction in stomatal conductance and thus transpiration. Both C₃- and C₄-plants are affected in this way. An average reduction of 20% of stomatal conductance has been found with a doubling of the current CO₂ concentration (Drake et al., 1997). However, effects of soil water availability and leaf area index reduce the impact on total transpiration.

There is a third primary effect of CO₂ enrichment, which is the reduction of dark respiration because CO₂ and O₂ are mutually competitive substrates on the ribulose biphosphate carboxylase enzyme for ribulose biphosphate followed by a reduction in activity of respiratory enzymes (Ogren, 1984; Bunce, 1994). Maintenance respiration has been found to be reduced by 20% for a doubling of the current atmospheric CO₂ concentration (Drake et al., 1997).

The resulting effects of these primary responses of plants to rising atmospheric CO₂ concentration are increasing resource use efficiencies for radiation, water and nitrogen. The highest response is seen for water use efficiency, which is affected positively by all three factors and increased in

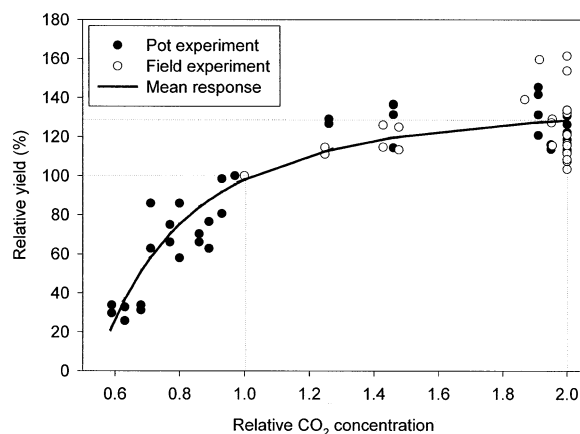


Fig. 3. Relative effects of CO₂ concentration on wheat grain yield in experiments. Ambient CO₂ is set to 1. Open symbols represent data from field experiments (OTC, FACE), filled symbols represent data from pot or glasshouse experiments. The solid line shows the mean estimated response (Downing et al., 2000).

both C₃ and C₄ species. The water use efficiency in wheat has been found to increase by about 50 to 60% for a doubling of current CO₂ concentration (Downing et al., 2000). Some of the CO₂ effects are enhanced or modified by changes in plant structure (Pritchard et al., 1999).

The observed response of grain yield in wheat to variation in CO₂ concentration is illustrated in Fig. 3. This graph draws on data from 12 whole-season studies with different CO₂ concentrations under a wide range of experimental conditions, from pots in growth chambers or glasshouses to open top chambers (OTC) or free air CO₂ enrichment (FACE) facilities (Downing et al., 2000). Fig. 3 shows a mean yield increase of 28% for a doubling of current CO₂ concentrations. There is some variation in the growth response of C₃ species to enhanced CO₂. A large proportion of this variation can be attributed to warm temperatures enhancing the relative CO₂ response (Dahlman, 1993).

3.2. Effect of other environmental changes

The increase in CO₂ concentration is not the only environmental factor that may affect agriculture in the future. Increased surface receipts of

UV-B radiation due to stratospheric ozone depletion, and increased tropospheric ozone concentration will influence future agricultural performance and will condition agricultural response to climate change. Experiments have shown that European crops are generally resistant to increased UV-B radiation (Allen et al., 1999; Papadopoulos et al., 1999). A doubling of tropospheric ozone concentration has been shown to reduce wheat yields by 9% (van Oijen and Ewert, 1999). However, the relative yield reduction from ozone was lower with increased CO₂ concentration.

3.3. *Climate effects on system productivity*

3.3.1. *Temperature*

At middle and higher latitudes of Europe, global warming will extend the length of the potential growing season, allowing earlier planting of crops in the spring and earlier maturation and harvesting. Less severe winters will also allow more productive cultivars of winter annual and perennial crops to be grown. This is of particular importance for C₄ species since the pyruvate phosphate dikinase is sensitive to low temperature (Edwards, 1986). This enzyme plays a key role in the regeneration of phosphoenol pyruvate, the acceptor of CO₂ in C₄ species.

Cropping areas may expand northwards in countries such as Finland and Russia. The shifts will be most pronounced along the current margins for production of specific crops. In Finland Carter et al. (1996) found a northward shift of areas suitable for spring cereals of 120–150 km °C⁻¹ increase in annual mean temperature. Spatial shifts northwards and into central Europe has also been estimated for warmer season crops like grain maize and grapevine (Kenny and Harrison, 1992; Kenny et al., 1993).

In warmer, lower latitude regions of Europe, increased temperatures increase respiration, resulting in less than optimal conditions for net growth. Another important effect of high temperature is accelerated development, resulting in hastened maturation of determinate crops and reduced yield (Rötter and van de Geijn, 1999).

3.3.2. *Water*

Agriculture of any kind is strongly influenced by the availability of water. Climate change will modify rainfall, evaporation, runoff, and soil moisture storage. Changes in total seasonal precipitation or in its pattern of variability are both important.

Agriculture is already the largest consumer of water resources in semiarid regions (Yeo, 1999). The demand for water for irrigation is projected to rise in a warmer climate, increasing the competition between agriculture and urban as well as industrial users of water (Arnell, 1999). More water will be required per unit area under drier conditions, and peak irrigation demands are also predicted to rise due to more severe heat waves (Parry, 2000).

3.3.3. *Climatic variability*

Extreme meteorological events, such as spells of high temperature, heavy storms, or droughts, can severely disrupt crop production. Recent studies have considered possible changes in the variability as well as in the mean values of climatic variables (Semenov and Porter, 1995). Where certain varieties of crops are grown near their limits of maximum temperature tolerance, heat spells can be particularly detrimental (Ferris et al., 1998).

3.3.4. *Soil fertility and erosion*

Soil organic matter plays a key role in building and sustaining soil fertility, affecting physical, chemical and biological soil properties (Rounsevell et al., 1999). Increased temperature will increase the turnover rate of organic matter. The effects are likely to be highest during winter time, and increased turnover may lead to buildup of inorganic nitrogen in the soil and increased risk of nitrate leaching. The overall effect of climate change on soil organic matter levels and nitrate leaching will depend on how climate change affects soil moisture during the summer season (Leirós et al., 1999), on the counteracting effect of increased carbon inputs from the growth-enhancing effect of increased atmospheric CO₂, and on increased nitrate uptake by the vegetation (Ineson et al., 1998a,b). Depending on the actual situations this may lead to enhanced CO₂ emissions,

which probably will be most pronounced from peat soils and also affect the use of these soils for agricultural purposes (Hartig et al., 1997; Chapman and Thurlow, 1998). N_2O emissions may also be enhanced under some conditions affected by both changes in temperature, soil moisture and carbon input (Ineson et al., 1998b; Kamp et al., 1998).

Drier soil conditions will increase the vulnerability to wind erosion, especially if winds intensify. Higher evaporation will also increase the risk of salinisation of soils in regions where total rainfall is restricted (Yeo, 1999). An expected increase in rainfall, caused by stronger gradients of temperature and pressure and more atmospheric moisture, may result in a larger frequency of high intensity precipitation events, causing increased soil erosion (Favis-Mortlock and Guerra, 1999).

3.3.5. *Crop protection*

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 (von Tiedemann, 1996), although there have been very few studies on the effect of climate change on the interaction of crops and diseases (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 (Cammel and Knight, 1992). 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).

Altered wind patterns may change the spread of both wind-borne pests and of the bacteria and fungi that are the agents of crop disease. Some pests also act as vectors of plant viruses, and there are indications that problems with virus-vector nematodes may increase with climate change (Neilson and Boag, 1996).

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 (Patterson, 1995; 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.

The control of weeds, pests and diseases is also likely to be affected by these changes (Patterson, 1995; Coakley et al., 1999). Observed changes in leaf surface characteristics due to CO_2 effects may interfere with herbicidal control and with uptake of systemic fungicides. The effectiveness and duration of pesticide control is also affected by environmental conditions, such as temperature, precipitation, wind and air humidity. This may have both positive and negative effects on efficacy.

3.3.6. *Constraints on management*

The weather directly affects the ability to manage soils, crops and livestock properly. Detrimental soil compaction can occur, if tillage and traffic is performed when the soil is too wet (Soane and van Ouwerkerk, 1994). Soil workability is one of the key factors determining the spatial distribution of crops in Europe (Rounsevell et al., 1999). This means that currently wet areas would benefit from a drier climate in terms of machinery workdays (MacDonald et al., 1994). Similar benefits from a drier climate may occur for grasslands in wet temperate areas where poaching by grazing livestock is currently a problem (Rounsevell et al., 1996).

One of the most important restrictions in the more humid parts of northern Europe is the availability of dry weather conditions for harvesting cereal grains. A warmer climate will result in earlier harvests, which on its own will be beneficial in terms of the number of hours available for combine harvesting (Olesen and Mikkelsen, 1985).

3.4. *Agricultural systems response*

3.4.1. *Cereal and seed crops*

Cereals, oilseed and protein crops including pulses are generally determinate species, and the

duration to maturity depends on temperature and in many cases daylength. A temperature increase will therefore shorten the length of the growing period and reduce yields, if management is not altered (Porter and Gawith, 1999; Tubiello et al., 2000). Simple management options to counteract the warming effect are changes in sowing dates and use of longer season cultivars (Olesen et al., 2000; Tubiello et al., 2000). This warming effect is counteracted by the CO₂ fertilisation effect, which also will lead to increased symbiotic nitrogen fixation in pulses (Serraj et al., 1998).

A climatic warming will expand the area of all cereals northwards. The cropping area of the cooler season seed crops (e.g. pea, faba bean and oil seed rape) will probably expand northwards into Fenno-Scandinavia with a climate warming. There will also be a northward expansion of warmer season seed crops (e.g. soybean and sunflower). An analysis of the effect of climatic change on soybean yield for selected sites in western Europe suggests mainly an increase in yield (Wolf, 2000a).

Yield reductions with increasing temperature have been predicted for eastern Europe, and the yield variability may increase, especially in the steppe regions (Alexandrov, 1997; Sirotenko et al., 1997). However, these estimates did not include the direct effect of increasing CO₂.

Table 4 gives a summary of mean relative changes in yield for a number of grain crops in Europe based on published studies. The scenarios and the adaptation options used in these studies differ considerably, but all studies have included both the climate change effect and the direct effects of CO₂ concentration on crop production. All studies indicate a larger yield increase or a smaller yield reduction in northern Europe compared with southern Europe. The results for sunflower seem to indicate yield reductions. However, most of these results were based on only one cultivar (Harrison and Butterfield, 1996), and it is likely that changes in management and cultivar selection will reduce these yield decreases.

Future cereal crop production will depend not only on climate change effects, but also on further developments in technology and crop manage-

Table 4

Relative increase (per cent) in water-limited or irrigated yield of crops in regions of Europe for scenarios of climate change for year 2050 and for a doubling of atmospheric CO₂ concentration relative to 1990 level

Crop	2050		2 × CO ₂		Source
	North	South	North	South	
<i>Rainfed</i>					
Wheat	22	18	23	−16	c, e, g, h, i
Grain maize	104	−28	140	−36	b, e
Sunflower	−25	−38	−40	−14	a, i
Soybean	65	45	—	—	j
Potato	20	8	—	—	k
Grapevine	24	12	—	—	f, g
<i>Irrigated</i>					
Grain maize	158	−11	231	−21	b, i
Soybean	81	17	—	13	i, j
Potato	23	1	—	—	k

Only estimates including both climate and CO₂ effects on crop production are considered. The estimates were taken from simulation runs including simple adaptation measures such as changed sowing date, where possible. The North region here is equivalent to regions 1, 2, 5, 6 and northern parts of region 5 in Fig. 1. The South region includes regions 4, 7 and southern parts of region 5. The studies include: (a) Harrison et al. (1995), (b) Wolf and van Diepen (1995), (c) Semenov et al. (1996), (d) Hulme et al. (1999), (e) Alexandrov and Hoogenboom (2000), (f) Bindi et al. (2000), (g) Harrison et al. (2000a), (h) Iglesias et al. (2000), (i) Tubiello et al. (2000), (j) Wolf (2000a), (k) Wolf (2000b).

Table 5

Wheat production (Mt) in European regions in 1995–1999 and possibilities for increased production due to yield gap and due to climate change by 2050, given no change in wheat area

Region	Production 1995–1999	Yield gap	Climate change 2050
(1) Nordic	3	0	1
(2) British Isles	16	5	5
(3) Western	62	9	16
(4) Mediterranean	15	10	5
(5) Alpine	2	1	1
(6) North eastern	12	14	6
(7) South eastern	16	12	5
(8) Eastern	52	183	42
Total (regions 1–8)	178	234	79
Regions 1–5	96	25	26
Regions 6–8	81	209	53

The yield gap is defined as the difference between maximum obtainable yields as calculated by Rabbinge and van Diepen (2000) and yields in 1995–1999. The climate change effect for year 2050 was estimated by multiplying the relative yield increases by the maximum obtainable yields. Separate yield increases for South and North Europe were taken from Table 4.

ment to increase productivity. This technology effect may be assessed by comparing current yields for wheat in Table 3 with the simulated yields under optimal management. This difference defines the yield gap. Table 5 compares the estimated yield gap for wheat with the estimated yield increase from climate change for year 2050 using the estimates from Table 4. The relative yield increase from climate change in eastern Europe (region 8) was set to the same value as for south Europe. The yield increase from climate change in regions 1–5 is of the same magnitude as the yield gap, whereas the yield gap for regions 6–8 is four times higher than the yield benefits obtained from global change. The possibilities for increased yields in eastern Europe through technological changes thus far outweigh the possible effect of climate change.

It has been claimed that the yield effects of increasing atmospheric CO₂ is relatively insignificant in comparison to effects of technology (Amthor, 1998). Whereas this may be true when comparing with technology changes in USA and western Europe over the past century, it does not necessarily hold when yields are not limited by technology, but by environmental constraints, e.g. wheat production in the Mediterranean region.

3.4.2. Root and tuber crops

Potato, as well as other root and tuber crops, is expected to show a large response to rising atmospheric CO₂ due to its large below ground sinks for carbon (Farrar, 1996) and apoplastic mechanisms of phloem loading (Komor et al., 1996). 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 (Table 4), but an almost constant increase in yield variability is predicted for the whole Europe, which raises the agricultural risk for this crop. However, available crop management strategies (i.e. advanced planting and the cultivation of earlier varieties) seem effective in overcoming these changes (Wolf, 2000b).

Root crops such as sugar beet may be expected to benefit from both the warming and the increase in CO₂ concentrations, as these crops are not determinate in their development and an extended growing season will increase the duration of growth, provided sufficient water is available.

3.4.3. Horticultural crops

Horticultural crops include both vegetables and ornamental crops, either field-grown or

grown under protected conditions. The main effects of a climatic warming anticipated for protected crops are changes in the heating and cooling requirements of the housing.

Most field-grown vegetables are high value crops, which are grown under ample water and nutrient supply. Therefore they mainly respond to changes in temperature and CO₂. Responses to these factors vary among species, mainly depending on the type of yield component and the response of phenological development to temperature change. For determinate crops like onion, warming will reduce the duration of crop growth and hence yield, whereas warming stimulates growth and yield in indeterminate species like carrot (Wheeler et al., 1996; Wurr et al., 1998). For lettuce, temperature has been found to have little influence on yield, whereas yield is stimulated by increasing CO₂ (Pearson et al., 1997).

For many field-grown vegetable crops, increasing temperature will generally be beneficial, with production expanding northwards. A temperature increase will in some areas offer the possibility of a larger span of harvesting dates thus giving a continuous market supply during a longer period of the year. For cool-season vegetable crops such as cauliflower, large temperature increases may decrease production during the summer period in southern Europe due to decreased yield quality (Olesen and Grevsen, 1993).

3.4.4. *Perennial crops*

Grapevine is a woody perennial plant, which requires relatively high temperatures. A climatic warming will therefore expand the suitable areas northwards and eastwards (Kenny and Harrison, 1992; Harrison et al., 2000a). 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; Bindi and Fibbi, 2000). However, yields in grapevine may be strongly stimulated by increased CO₂ concentration without causing negative repercussions on the quality of grapes and wine (Bindi et al., 2001).

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).

The need to reduce greenhouse gas emissions has encouraged the growing of energy crops such as willow and *Miscanthus* (Kahle et al., 2001). These crops are established over a period of a few years, and subsequently harvested every year or every few years. These crops are generally indeterminate and will be favoured by conditions that extend the growing season and increase the light or water use efficiencies. For willow production in the UK a temperature increase of 3 °C may increase yields by up to 40% (Evans et al., 1995).

3.4.5. *Forage crops and grasslands*

Forage crops include cereals for silage and some root crops. When these crops are grown as forage crops, the yield components and the quality criteria change. The effects of climate change on production and quality of wheat whole crop silage depends on the relative magnitudes of changes in CO₂ concentration and temperature (Sinclair and Seligman, 1995). If the CO₂ effect dominates, then a yield increase but a decrease in digestibility will result, and vice versa if the temperature increase dominates. Yields of indeterminate crops such as sugar beet and of silage maize can be expected to show a larger increase, especially in northern Europe, than the yield of whole crop cereals. This will lead to changes in the types of forage crops grown, with an increase in forage maize production in northern areas (Davies et al., 1996; Cooper and McGechan, 1996).

Permanent grasslands occupy a large proportion of the European agricultural area (Table 2). The type of grassland varies greatly within Europe from grass and shrub steppes in the Mediterranean region to mires and tundra in northern Europe. Temperate grasslands vary from intensively managed monocultures to species-rich communities with local variations depending on soil type and drainage. The different species will differ in their responses to CO₂ and climate change,

resulting in alterations in the community structure of grasslands in the future. However, the management and species-richness of grasslands may increase resilience to change (Duckworth et al., 2000). Legumes, which fix nitrogen from the atmosphere, may benefit more from a CO₂ increase than non-fixing species (Schenk et al., 1995). This has experimentally been found to lead to larger nitrogen inputs to grass-clover swards (Zanetti et al., 1996).

Intensively managed and nutrient-rich grasslands will respond positively to both the increase in CO₂ concentration and to a temperature increase, given that water supply is sufficient (Thornley and Cannell, 1997). The direct effect of a doubling of CO₂ concentration may alone cause a 20–30% increase in productivity of N-rich grasslands (Jones et al., 1996; Cannell and Thornley, 1998). The importance of water management including drainage may, however, be even more important under changed climatic conditions in northern Europe (Armstrong and Castle, 1992). The positive effect of increased CO₂ on biomass production and water use efficiency can be offset by climate change, depending on local climate and soil conditions (Topp and Doyle, 1996a; Riedo et al., 1999). These effects will also determine the spatial distribution of agricultural grassland (Rounsevell et al., 1996). The response of intensively managed grasslands to temperature change may also depend on the response of grass growth to the cutting or grazing regime used. A proper evaluation of these effects requires that the source and sink relations are considered, in particular as affected by phenology and defoliation (Schapendonk et al., 1998).

There is controversy over the response of N-poor and species-rich grassland communities. Experimental studies in such grasslands have shown little response or even a reduction in production with CO₂ enrichment (Korner, 1996). Simulation studies have on the other hand shown that this is just a transient response, and that the long-term productivity increase of N-poor grassland ecosystems may relatively be much larger than that of N-rich systems (Cannell and Thornley, 1998). This is caused by a reduction in nutrient losses and an increase in nitrogen fixation by elevated CO₂ (Lüscher et al., 2000).

3.4.6. *Livestock*

Climate and CO₂ 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 CO₂ is enhanced (Topp and Doyle, 1996b).

Livestock production may be negatively affected in the warm months of the currently warm regions of Europe, as has been found for parts of the USA (Klinedienst et al., 1993). 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. Climate change may, however, affect requirements for insulation and air-conditioning and thus increase or decrease housing expenses in different regions. The impact of climate change on housing depends not only on temperature, but also on radiation and wind (Cooper et al., 1998). Climate change will also affect the turnover and losses of nutrients from animal manure, both in houses, storages and in the field. An example of this is the increase in ammonia volatilisation with increasing temperature (Sommer and Olesen, 2000).

4. *Adaptation and mitigation*

4.1. *Adaptation*

To avoid or at least reduce negative effects and exploit possible positive effects several agronomic adaptation strategies for agriculture have been

suggested. A number of different methods for studying adaptation to climate change have been applied in literature (Mendelsohn and Dinar, 1999). These include the testing of adaptation options as specified in agroecosystem models, possibly linked with farm level economic models, and the use of agroecological zone analysis or Ricardian models. The latter methods compare current farm practices and performance with current climate and climate variability and based on this, response functions of farm value to climate change can be generated.

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; Rounsevell, 1999). 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 land use changes (Parry et al., 1999). Indeed the possibility exists for a global increase in agricultural productivity, if adaptation is at least partially effective in lower latitude countries, and the productivity increase in mid and higher-latitude agriculture is exploited. However, this may have negative effects on farm income through decreases in prices (Reilly, 1999).

The agronomic strategies available include both short-term adjustments and long-term adaptations. The short-term adjustments have been studied using agroecosystem models, but often not in a systematic way (Easterling, 1996). Both short-term adjustments and long-term adaptations are included in the Ricardian models, but not in an explicit way. This makes these models unsuitable for exploring specific adaptation capacities (Schneider et al., 2000).

4.1.1. Short-term adjustments

Short-term adjustments to climate change 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.

For spring crops climate warming will allow earlier planting or sowing than at present. Earlier planting in spring increases the length of the growing season; thus earlier planting using long season cultivars will increase yield potential, provided moisture is adequate and the risk of heat stress is low. Otherwise earlier planting combined with a short-season cultivar would give the best assurance of avoiding heat and water stresses (Tubiello et al., 2000). Winter cereals are required to have reached a specific growth stage before the onset of winter to ensure winter survival, and they are often sown when temperatures approach the time when vernalization is most effective (Harrison and Butterfield, 1996). This may mean later sowings in northern Europe under a climatic warming (Harrison et al., 2000b; Olesen et al., 2000).

External inputs are used to optimise the production of crops in terms of productivity and profitability. The use of fertilisers is generally adjusted to the removal of nutrients by the crop and any losses of nutrients that may occur during or between growing seasons. The projected increases in atmospheric CO₂ concentration will increase crop growth and nitrogen uptake by the crop, and thus increase the need for fertiliser applications. On the other hand climatic constraints on yields may lead to less demand for fertilisers. Changes in climate may also cause larger (or smaller) losses of nitrogen through leaching and gaseous losses. This may also lead to changes in the demand for fertiliser (Porter et al., 1995). The use of pesticides reflects the occurrence of weeds, pests and diseases. Global warming will, in many areas, lead to a higher incidence of these problems and thus to a potentially larger use of pesticides. The use of pesticides can, however, be kept low through the adoption of integrated pest management systems, which targets the control measures to the observed problem.

Current fertiliser and pesticide practices are partly based on models and partly on empirical functions obtained in field experiments. These models and functions are updated regularly with new experimental evidence. This process will probably capture the response of changes in the environment through CO₂ and climate. It is im-

portant that agricultural researchers and advisors are aware of the possible impact of global change on the use of external inputs, so that older empirical data are used with caution.

Several water-conserving practices are commonly used to combat drought. These may also be used for reducing climate change impacts (Easterling, 1996). Such practices include conservation tillage and irrigation management. Conservation tillage is the practice of leaving some or all the previous season's crop residues on the soil surface. 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. Irrigation management can be used to improve considerably the utilisation of applied water through proper timing of the amount of water distributed.

4.1.2. *Long-term adaptations*

Long-term adaptations refer to major structural changes to overcome adversity caused by climate change.

Changes of land use result from the farmer's response to the differential response of crops to climate change. Studies reported by Parry et al. (1988) for central Europe showed an 'optimal land use' in which the area cultivated with winter wheat, maize and vegetables increased, while the allocation to spring-wheat, barley, and potato decreased. Changes in land allocation may be used also to stabilise production. In this case crops with high inter-annual variability in production (e.g. wheat) may be substituted by crops with lower productivity but more stable yields (e.g. pasture). Crop substitution may be useful also for the conservation of soil moisture.

Crop breeding may be considered as another adaptive response to climate change by the use of both traditional and biotechnological techniques that allow the introduction of heat and drought resistant crop varieties. Collections of genetic resources in germ-plasm banks may be screened to find sources of resistance to changing diseases and insects, as well as tolerances to heat and water stress and better compatibility to new agricultural technologies. Genetic manipulation may offer possibilities for more rapid adaptation to stresses

aggravated by climate change (Goodman et al., 1987).

New land management techniques (minimum tillage, stubble mulching, etc.) or management strategies (e.g. irrigation scheduling) may be used to improve irrigation efficiency in agriculture (Kromm and White, 1990). Moreover a wide array of techniques (such as inter-cropping, multi-cropping, relay cropping etc.) can be also useful to improve water use efficiency. Restrictions in the availability of good-quality irrigation water may increase the need for such techniques.

Nutrient management will need to be adapted to changes in the turnover of nutrients in soils, including losses. It may thus be necessary to revise standards of soil nitrogen mineralisation and the efficiency of use of animal manure and other organic fertilisers. There is a range of management options that will affect the utilisation of fertilisers and manure, including fertiliser placement and timing, changed crop rotations and use of cover crops.

Changes in farming systems may be necessary in some areas for farming to remain viable and competitive. In many regions of Europe, farms have become specialised in either specific livestock or arable farming. This specialisation is often linked to the local soil and climate conditions. Dairy farming is thus often located in conditions which ensure a proper water supply to the grass and forage crops during summer, as continuity of feed supply is essential. Specialised pig or poultry production on the other hand only requires access to cereals and protein feeds, which are easier and cheaper to transport. These farms are therefore less reliant on local feed supply, but often have restrictions on the disposal of urine and manure from production. Specialised arable farms with production of vegetables, cereals, seed crops, fruits etc. often have only a few species on the farm, depending on soil and climate conditions. These specialised farms, especially dairy farms and arable farms, will probably respond more to climate change than mixed farms. On mixed farms with both livestock and arable production there are more options for change, and thus a larger resilience to change in the environment.

4.2. Mitigation

Agriculture has a range of options to further reduce greenhouse gas emissions, either directly by reducing energy use and emissions of methane and nitrous oxide or by substitution of fossil energy use and carbon sequestration in soils. Methane emissions can be reduced through changes in animal feeding strategies and through changes in manure handling, e.g. production of biogas from animal slurry. Nitrous oxide emissions may be reduced through changes in manure handling, more efficient nitrogen use and changes in crop and soil management (Rosenzweig and Hillel, 2000). A number of agricultural management options including conservation tillage practices, crop residue management, cover crops and altered crop rotations have been suggested as measures for carbon sequestration in soils (Smith et al., 2000). Advantage should be taken of the fact that some of the measures simultaneously may reduce the net emission of several greenhouse gases. However, climate change may affect the emission of greenhouse gases from agriculture (Mosier, 1998).

4.3. Relations to other sectors

The major beneficiary from agriculture and horticulture is the food industry. This industry is becoming more oriented towards the global market, a trend that is being strengthened by the liberalisation of world trade. Parts of the food industry will therefore be less reliant in the future on the local supply of produce and demand for products. However, a small part of the European food industry relies on local food brands (specialities), some of which are registered and protected by EU regulation (Obst et al., 1996). Such local food specialities may be particularly susceptible to climate change, because they rely on high quality products, which often have a long local tradition coupled with favourable natural conditions.

Land use is likely to change in the future, driven by agricultural policy and demand for foods, recreational areas, environmental protection, urbanisation, etc. (Bouma et al., 1998). All these factors will probably to some extent be influenced by global change.

Agriculture is a major user of water resources for irrigation, especially in southern Europe (Table 2). The anticipated changes in climate suggest warmer and drier conditions for this region during summer. This will enhance the demand for freshwater, especially for agriculture and human consumption (Vörösmarty et al., 2000). It is likely that this will lead to increasing restrictions on irrigation in agriculture and horticulture.

5. Implications for policy and research

Two current trends are considered to continue to dominate the agenda for agricultural policy in Europe during the first part of the 21st century. These are (1) the change to market economy and resulting increasing efficiencies and productivity in the agriculture of the former Soviet Union and eastern Europe, and (2) the continued trade liberalisation enforced by institutions like the world trade organisation, which from 1995 have included agriculture in the liberalisation efforts. These changes along with the reform of the EU CAP during the 1990s has considerably reduced the budgetary costs as the driving force in EU's agricultural policy (Matthews, 1996). This means that resources previously tied up in price support can now be made available to be invested in environmental schemes (Potter and Goodwin, 1998).

In addition to these current trends, European agricultural policy will need to consider support for the adaptation of European agriculture to climate change. This may be done by encouraging as much as possible the flexibility of land use, crop production, farming systems and so on. This would be feasible utilising the main agricultural resources (Table 6). 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). Policy should include aspects related to both adaptation and mitigation. Parts of the agricultural land may be used for

carbon storage and substitution of fossil fuel, and there is a large scope for reducing greenhouse gas emissions from agriculture (Mosier, 1998).

Policies supporting the adaptation of agriculture to climate change may conflict with the current rigid structures of the EU CAP. Much of the financial support in the CAP is currently based on either the 1992 arable area or on country based quotas of livestock production. As climate change will affect the agricultural productivity differentially in various European regions, this will create an additional incentive to change the CAP towards a more flexible system, which is less dependent on regional production capacities.

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. In fertile areas and under favourable climatic conditions, priority will need to be given to production, but regulations must ensure that negative external environmental impact is kept within acceptable limits. In less fertile areas or areas with difficult climate, priority has to be given to financial support for the environmental and social functions of farming systems. Between these two extremes are a wide range of farming systems with varying degrees of justification for financial support for their social and environmental functions, and varying ability to

Table 6
Suggested resource based policies to support adaptation of European agriculture to climate change (modified from Easterling, 1996)

Resource	Policy
Land	<i>Reforming agricultural policy to encourage flexible land use.</i> The great extent of Europe cropland across diverse climates will provide diversity for adaptation
Water	<i>Reforming water markets and raising the value of crop per volume of water used to encourage more prudent use of water.</i> Water management, that already limits agriculture in some regions, is crucial for adapting to drier climate
Nutrients	<i>Improving nutrient use efficiencies through changes in cropping systems and development and adoption of new nutrient management technologies.</i> 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	<i>Support for integrated pest management systems (IPMS) should be increased through a combination of education, regulation and taxation.</i> There will be a need to adapt existing IPMS's to the changing climatic regimes
Energy	<i>Improving the efficiency in food production and exploring new biological fuels and ways to store more carbon in trees and soils.</i> 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	<i>Assembling, preserving and characterising plant and animal genes and conducting research on alternative crops and animals.</i> Genetic diversity and new genetic material will provide important basic material for adapting crops species to changing climatic conditions
Research capacity	<i>Encouraging research on adaptation, developing new farming systems and developing alternative foods.</i> Increased investments in agricultural research may provide new sources of knowledge and technology for adaptation to climate change
Information systems	<i>Enhancing national systems that disseminate information on agricultural research and technology, and encourages information exchange among farmers.</i> 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	<i>Integrating environmental, agricultural and cultural policies to preserve the heritage of rural environments.</i> Integration of policies will be required to maintain and preserve the heritage of rural environments which are dominated by agricultural practices influenced by climate

survive in free market trading conditions. Climate change will challenge the current balance between 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.

Policies to support adaptation and mitigation will need to be linked closely to the development of agri-environmental schemes. There are several reasons for this: (1) Climate change may enhance some of the current negative environmental effects of agriculture, and create new ones, (2) Climate change may threaten some of the traditional low-intensity farming systems, which are critical to nature conservation and protection of the rural environment (Bignal and McCracken, 1996), and (3) many of the measures to protect the agricultural environment will also reduce greenhouse gas emissions, e.g. by changes in cropping systems (Kuemmel et al., 1998) or adoption of conservation tillage practices (Uri, 1999). In terms of emissions reductions, priority need to be given to chain-oriented methods, i.e. methods that seek to increase carbon, nitrogen, water and energy use efficiencies in the whole food chain. Such methods should be implemented within other environmental policies that aim to increase resource use efficiencies (Oenema et al., 2001).

Climate change is not expected to significantly affect global food supply (Rosenzweig and Parry, 1994; Parry et al., 1999). These authors estimated that developing countries would be more severely affected by climate change than the developed countries that are generally located in temperate regions. This could lead to an increase in the importance of Europe for world food supply. However, estimates of future food production and demand are associated with high uncertainties (Döös and Shaw, 1999). The internal demand for agricultural products in EU is expected to stay flat for the coming period, whereas world food demand will increase given a population increase

to 9–10 billion in the next 30–40 years. In the longer term this may prove favourable for the farmers and the food industry in Europe, increasing the need for agricultural land.

Another factor that may become more important for land use in western Europe is the trend towards less intensive and organic farming systems, which will be less productive per unit area and thus require more land for the same output. Europe has capacity to significantly increase agricultural production (Rabbinge and van Diepen, 2000), and this capacity may be enhanced by global change due to increased crop productivity (Table 4). Part of this capacity may instead be directed towards organic farming systems, thus maintaining current agricultural production with less intensive production systems.

The EU CAP aims to maintain a viable rural society including the cultural heritage of many rural areas of Europe. This is partly a concern to maintain a proper management of the farmed countryside to protect biodiversity and prevent desertification and land abandonment, a concern that has traditionally been much stronger in Europe compared with the US (Potter and Goodwin, 1998). These efforts may be severely affected in regions, where the economic sustainability of traditional farming systems is being threatened by market forces, and which may be susceptible to effects of climate change. Such regions are probably most abundant in southern Europe.

Another aim of the CAP is to reduce environmental impact of agricultural production, e.g. through more judicious use of fertilisers and pesticides. This effort may also be affected by global change. Warmer conditions will generally increase the need for crop protection measures, leading to an increase in pesticide use. Warmer temperature and higher CO₂ concentration may lead to higher demands for nitrogen fertiliser. However, the effects on nitrogen losses to the environment are difficult to predict. Reducing such negative environmental impacts may lead to renewed use of agronomy, because cropping systems and cultivation methods will need to be adapted to new demands and to changing environmental conditions (Rabbinge and van Diepen, 2000).

Climate change related policy actions are especially urgent where there are long lead times or large investments at stake. This is the case for some of the large-scale irrigation systems, some of which already deplete available water resources. However, more information on the likely effects of climate change at the detailed regional level is needed before specific actions can be taken. This will also require use of much more elaborate models of adaptation to climate change (Reilly and Schimmelpfennig, 2000). Such regional impact assessments will need to consider the interactions with other sectors, in particular the hydrological sector, which in many European areas deliver water for irrigation in agriculture. This may not only affect Mediterranean countries severely. Also central and north European countries may be affected, e.g. through changes in seasonal changes of river-flow (Middlekoop et al., 2001). Regional impact and adaptation assessments should be encouraged, and their results should be collected at national and European levels to be used for formulating a climate change policy for the European agricultural sector.

The impact assessments need to be conducted in close collaboration with the stakeholders, and effort should also be put into increasing the awareness of individual farmers and decision makers on the issues of climate change and the need for adaptation of farming practices. Despite the public debate, the current awareness of climate change in the farming community appears to be low (Robinson, 1999). Studies on adaptation measures will also need to link the farm level decision making to the policy decisions made at local, regional or large scales (Chiotti and Johnston, 1995).

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. Studies should also investigate combined effects of adaptation and mitigation strategies, and 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.

6. Conclusions

The effects of global change are on the whole likely to increase productivity of European agricultural systems, because increasing CO₂ concentration will directly increase resource use efficiencies of crops, and because warming will give more favourable conditions for crop production in Northern Europe. However, this will require adaptation of current farming systems to new climatic conditions.

Climate change resulting from increased greenhouse gas emissions may be expected to reinforce the current trends of increasing cereal productivity in north-western Europe and reduced productivity in Mediterranean region. This could lead to intensification of farming systems in northern Europe and increased extensification in southern Europe.

The increased intensification of farms in northern Europe could in combination with an increase in the need for plant protection and increased turnover of soil organic matter lead to negative environmental side effects. 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.

Agricultural and environmental policies will have to support the adaptation of European agriculture to climate change, and to support the development of agricultural strategies to mitigate climate change through a net reduction in greenhouse gas emissions. Research should support such policies by studying combined effects of adaptation and mitigation strategies.

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