Climate Change & Agriculture

IN THE UNITED KINGDOM

PREFACE

Over the coming decades, agriculture worldwide faces the challenge of climate change, in addition to developments in social, technological and agricultural policy and practice. Agricultural businesses will need to adapt to the effects of changing climatic conditions, and at the same time modify best practice to reduce agriculture's continuing impact on global and local environments, thereby reducing contributions to greenhouse gases and reducing pollution of water systems.

The purpose of this booklet is to heighten awareness of climate change within the farming community. To do this, it draws on the results of £6 million worth of research on this subject, funded by MAFF. In some cases, enough is known about climate change to begin to formulate and apply strategies to cope with the expected changes. Where less is known, the knowledge of potential impacts is summarised. This forms a guide to the wealth of material appearing in scientific documents and the media.

This overview of the impact of climate change is based on the contributions of more than a dozen scientists. We believe the overall conclusions are warranted, but we are not unanimous in what should be done. Uncertainty is an essential aspect of science - and of farming.

Most of the research which forms the background to this booklet has addressed climate change in the context of England and Wales, although many of the results and conclusions are believed to be valid for the UK as a whole.

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This brochure was prepared for the UK Ministry of Agriculture, Fisheries and Food but does not necessarily represent the views of the Ministry.

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There is increasing evidence that global warming is caused by human activity: the release of greenhouse gases from burning fossil fuels, industrial processes and changes in land use. Of the man-made pollutants, carbon dioxide (CO_2) is the principal greenhouse gas, but methane, nitrous oxide and industrial chemicals are also important. Developed countries agreed in Kyoto in December 1997 to reduce their total emissions of greenhouse gases by 5% by 2010 relative to 1990 levels. The agreed international target for the UK is 12.5%. It also has a domestic goal of reducing CO_2 emissions to 20% below 1990 levels by 2010.

The past decade in the UK has been the warmest in over 300 years, and 0.5°C warmer than the average 1961-90 climate. Warm winters have reduced the number of frosts; warm summers have included record hot spells and high sunshine totals.

The climate change is likely to continue:

- CO_2 concentrations will continue to rise, from around 360 ppmv (parts per million by volume) at present to 450-600 ppmv by the 2050s. CO_2 has beneficial effects on agriculture by encouraging photosynthesis and reducing transpiration.

- Globally, sea level will rise by 10-50 cm by the 2050s. In the UK, sinking land could exacerbate the effect in the east and south, while rising land would partly offset it in the north. Agriculture and settlements in low-lying areas could be affected by incursion of salt water into aquifers, coastal erosion and coastal flooding.
  If coastal storms become more intense and/or frequent the increase in combined risk of flooding could be significant.

- By the 2050s, the UK is likely to be about 1-2°C warmer than the present 1961-90 average. Winters are expected to warm more than summers. Hot spells, such as occurred in the 1995 summer would show a dramatic rise in frequency. Higher temperatures increase evaporation rates, reduce frost hazards and winter chilling, lengthen the growing season and accelerate plant growth. Heat stress may affect some crops.

- Changes in precipitation (rainfall and snowfall) are difficult to calculate, but average seasonal changes are expected to be relatively modest (increases or decreases of 10%), at least until the 2050s. More rainfall is expected to fall in intense events, however, increasing runoff and the risk of erosion. Precipitation patterns might also become more variable, resulting in greater probabilities of floods and droughts - but this is still very uncertain. The combination of higher temperatures and changed precipitation regimes has implications for water balances and organic content of soils, with consequences for irrigation demand and use.

The impact of climate change on arable crops, horticulture, weeds, pests and diseases, grasslands and livestock includes changes in the location of agricultural activities, earlier development and growth, changed yields and quality.

For arable crops, the overall effect on yield of increased CO_2 and temperature will be broadly neutral. Nutrient requirements will increase relatively little (perhaps 10%).The range of current crops will move northward and marginal crops such as maize may increasingly penetrate southern UK. New crop varieties, suitable for the changed climate, may need to be selected.

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Greater extremes of climate pose threats that are difficult to predict and adjust to but will, as now, have large effects. A rise in sea level will have local but agriculturally important impacts which may not be overcome easily by new crop varieties.

High quality horticultural crops will be more susceptible to changing conditions than arable crops. Field vegetables will be particularly affected by changes in temperature. Those species most likely to benefit commercially from higher temperatures are phaseolus bean, onion and sweetcorn. The availability of water is critical to the production of quality fruit and vegetables; a decrease in supplies will focus attention on increased efficiency of water use.

Intensive grassland agriculture will be affected by direct effects on grass yield and forage production and also indirectly by effects on other crops and their potential to provide economic and sustainable returns. The relative suitability for different types of livestock throughout the UK is unlikely to change significantly. Production systems involving ruminants at grass or in naturally ventilated housing are likely to adapt to the changes expected in the next 50 years. Intensive livestock (pigs and poultry) are at risk of increased heat stress. Thermal stress influences productivity and health. Disease transmission is likely to increase from greater exposure, e.g. from faster growth of pathogens in the environment and more efficient and abundant insect vectors. There may be consequences for food quality.

The potential for ***soils*** to support agriculture, and the future distribution of land use, will be strongly influenced by changes in the soil water balance. Where soil water deficits increase, crop productivity will suffer, and for some crops this is likely to result in the increased use of irrigation. Conversely, drier soil conditions may favour arable agriculture in the currently wetter regions of the UK as a result of improved soil workability, and diminished poaching risk in grassland areas. Soil organic matter levels will depend on the balance between carbon inputs to soils and the rate of loss resulting from decomposition.

Weeds evolve rapidly to overcome control measures. Very short-lived weeds and those that spread vegetatively (such as couch and creeping buttercup) evolve fastest. The rate of evolution will increase in hotter, drier conditions and in 'extreme' years. This increased rate of evolution could lead to some types of herbicide tolerance becoming more common.

Predicted climate changes are likely to increase the UK range of many native pests and diseases but decrease the range of others. Native species that are not currently economically important may become so, while the significance of other pests and diseases may diminish. Surveillance and eradication procedures for some alien pests (e.g. the Colorado beetle) and diseases are likely to become increasingly important.

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Farm management will be affected by climate change. Soils, climate, markets, technology, capital and policy all influence the location and type of farming. In determining future cropping in a warmer climate, it is extremely important to take into account increased climatic variability and the pattern of rainfall (amount, distribution and intensity). Unfortunately, these are the hardest features of climate change to predict. Increased climatic variability will require closer crop monitoring, scheduling of work peaks to ensure that crops are harvested and established in the appropriate conditions, and provision for greater fluctuations in markets and income.

Agriculture in the UK is highly adaptable, as demonstrated by improved technology, sustained output and profitability over the last 50 years. The impact of climate change depends on the mix of global effects on demand and production and the local effects of warmer temperatures and altered growing conditions. The policy and economic framework for European agriculture could significantly mitigate the impact of climate change.

Significant uncertainties remain in our understanding of climate change, its impacts and the most effective responses.

Nevertheless, farmers should consider three strategies:

- maintain or enhance their ability to adapt to change;
- anticipate climate change in some decisions;
- take steps to reduce emissions of greenhouse gases.

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Climate change affects agriculture - and agriculture contributes to climate change. This chapter presents the evidence for this, reviews trends in the UK climate and describes possible future climates (including sea level rise). Agriculture's contribution to greenhouse gas emissions is also summarised.

Projections of climate change for individual regions are still uncertain. Although reductions in greenhouse gas emissions have been agreed in principle (see Box 1.1), they will have a relatively small effect on climate change in the medium term. We must be prepared for the potential changes that may affect crops and livestock.

Box 1.1
Reducing greenhouse gas emissions

Negotiating reductions in greenhouse gases culminated in a last-minute agreement in Kyoto at the third Conference of Parties of the Framework Convention on Climate Change. Representatives from 160 countries agreed on legally binding limits for carbon dioxide, methane, nitrous oxide, fluorocarbons and sulphur hexafluoride for all developed countries. The reductions will average about 5% for the years 2008-12 compared with 1990 levels. Special treatment of individual countries was accepted because of particular national circumstances: some will even increase emissions. The European target is an 8% reduction overall. National commitments within the EU will be negotiated in 1998.

Other key agreements concern trading emissions between developed countries and technology transfer to developing countries through a 'clean development mechanism'. Targets for reductions in emission in developing countries were the subject of intense debate, but no agreement was reached.

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1.1
IS THE GLOBAL CLIMATE CHANGING?

Representing the work of over 2000 scientists, the Intergovernmental Panel on Climate Change (IPCC), concluded that 'the balance of evidence, from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate.' (Houghton *et al.* 1996)

The evidence for this conclusion of the IPCC rests on (i) the physical effect of greenhouse gases on the atmosphere, (ii) projections from global climate models, and (iii) observed climatic trends.

Elevated concentrations of greenhouse gases

The *greenhouse effect* is a popular term used to describe how certain gases in the atmosphere insulate the planet. These 'greenhouse' gases are relatively transparent to sunlight (incoming short-wave radiation), but absorb heat from the Earth's surface (outgoing long-wave radiation). Heat that would otherwise escape to space is trapped by these gases within the lower levels of the atmosphere. This 'thermal blanket' maintains surface temperatures higher than they would be if the gases were absent. The natural greenhouse effect already keeps the Earth over 30°C warmer than it otherwise would be; increasing concentrations of greenhouse gases will warm the Earth still further.

Greenhouse gases include water vapour, CO_2, tropospheric ozone, nitrous oxide, methane and industrial chemicals such as chlorofluorocarbons (see Table 1.2). Changes in CO_2 are the most important, contributing about 60% to global warming. Methane and nitrous oxide, for which agriculture is an important source, contribute about 15% and 5% respectively. Alteration of the atmosphere by human activities has continued since pre-industrial times. However, the volume of greenhouse gases emitted worldwide has increased enormously in recent decades.

Figure 1.1 illustrates the rise in CO_2 in the atmosphere. Pre-industrial concentrations were about 275 ppmv, compared with 360 ppmv at present.

Projected concentrations of greenhouse gases will depend on trends in resource use and policies to limit greenhouse gas emissions. What new energy technologies will emerge? How large will the human population be? What will be the extent of agriculture and forestry? Accurately predicting these changes one or two generations into the future is unlikely. It is therefore necessary to consider the future climate in terms of a number of different scenarios rather than firm pronouncements.

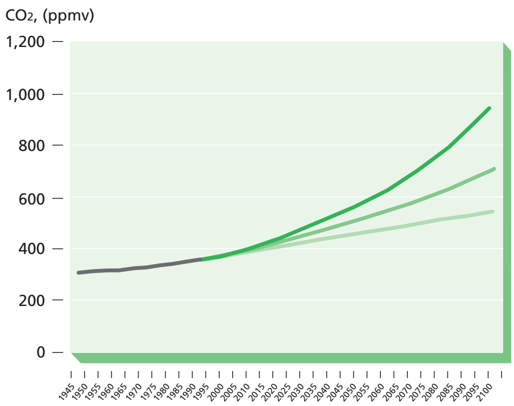

Figure 1.1: CO_2 concentrations in the atmosphere. Observed concentrations (grey line) shows an increase from less than 280 ppmv at the beginning of the industrial revolution to over 360 ppmv at present. Projected concentrations depend on population, economic and technological assumptions. Three scenarios are shown from the IPCC (corresponding to high, mid and low projections). Source: data from MAGICC, CRU, University of East Anglia.

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Rising global temperatures

Global average surface air temperatures have been compiled since 1856. The record shows a global warming of about 0.5°C over the 140-year period to 1999, with the warmest year occurring in 1998 and the warmest seven years all being recorded since 1983 (Figure 1.2). The decade 1990-99 has been 0.3°C warmer than the 1961-90 average. The geographical pattern of warming and the vertical structure of temperature change are beginning to resemble the patterns expected due to human influences on the global climate.

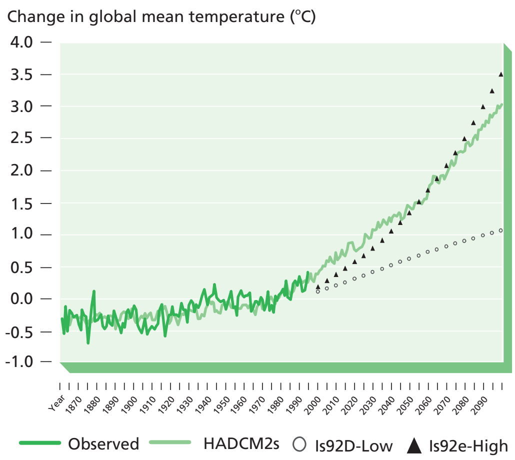

Figure 1.2: Departure of annual global-mean temperature from the 1961-90 average 1961-90 (dark green line) and projected global warming. The solid line is from the UK Hadley Centre global climate model (including aerosols). The high curve (triangles) and the low curve (circles) represent the range of uncertainty due to different scenarios of greenhouse gas emissions and climate sensitivity, based on a simpler global climate model, MAGICC. Source: data from the Met Office Hadley Centre, Bracknell and Climatic Research Unit, University of East Anglia.

Box 1.2
Role of sulphate aerosols

Sulphur dioxide is a by-product from the combustion of fossil fuels, especially coal. It is oxidised in the atmosphere to form sulphate particulates or aerosols. Aerosols only last for a few days in the atmosphere (compared to decades or centuries for greenhouse gases) before being washed out by precipitation, but they can have a major effect on the energy budget of the atmosphere.

Sulphate aerosols in the atmosphere tend to cool the Earth's surface. The size of this effect is highly uncertain, especially the indirect effect through changes to cloud reflectivity. The geographical distribution of future sulphur dioxide emissions depends on fossil fuel use and agreements regarding acid rain, both of which are highly uncertain.

At a global scale, sulphate aerosols offset some of the global warming caused by greenhouse gases, up to a few tenths of a degree Celsius (°C). Global sea level rise may be reduced by about 10%. At the regional scale, Figure 1.3 shows that the pattern of precipitation can be affected by the inclusion of aerosols in the global climate model. The more general conclusion is that simulation of precipitation changes is still uncertain.

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1.2 TRENDS IN THE UK CLIMATE

The climate of the UK is warmer now than it has been at any time since measurements began in this country in the 17th century. Winters have warmed by 1°C or more since the beginning of the 19th century and the last 20 years have seen an unusual sequence of warm summers. The past decade has been the warmest in the entire 340-year Central England Temperature record and 0.5°C warmer than the average 1961-90 climate. Fifteen exceptionally warm months in the UK occurred from 1990 to 1999, a period during which on average only three or four such extremely warm months should have been experienced in a constant climate.

This summer warming has led to more frequent hot days in the UK. The highest ever temperatures in the UK were recorded during August 1990, and in 1995 there were 23 days when the mean temperature in the Central England Temperature record exceeded 20°C, three more days than the previous record set in 1976. These warm summer temperatures have been associated with high sunshine totals. Three of the five sunniest summers in the 87-year England and Wales sunshine record occurred in the last decade: 1989, 1990 and 1995.

Quantities of precipitation (rainfall and snowfall) vary greatly in the UK from year to year and from decade to decade. There is little evidence of long-term trends in annual totals, except perhaps in Scotland, which has become wetter. There is, however, evidence of a changing seasonal distribution of precipitation over England and Wales, with winters getting wetter and summers drier. In this regard, 1995 was an exceptional year with a very wet winter and a very dry summer.

Windiness is an important aspect of the UK climate. The 116-year record of gales over the country suggests that the last ten years have witnessed a record number of severe gales, although the frequency of ordinary gale events has not changed. In 1990, for example, 20 severe gales occurred, two more than the previous highest total in 1916. Given the sporadic nature of major gales, it is too early to suggest that windstorms are increasing due to global climate change.

1.3 PROSPECTS FOR FUTURE CLIMATE CHANGE IN THE UK

A range of possible changes in climate may occur in the UK over the decades of the 21st century. This section describes the changes calculated from global climate model experiments performed at the Hadley Centre during 1995 and 1996. The Hadley Centre model simulates changes in atmospheric and oceanic circulation. Over the next 100 years the circulation of the North Atlantic, including the Gulf Stream, is assumed to remain relatively stable, although weakening slightly. Changes are expressed relative to the average 1961-90 climate and, unless otherwise stated, result from changes in greenhouse gases alone (i.e. without considering sulphate aerosols, see Box 1.2). The elements of climate change are listed in order of decreasing confidence in the predictions.

Carbon dioxide

Further increases in atmospheric CO_2 concentrations are among the most certain environmental changes in the next century. Concentrations by the 2050s are likely to be 450-600 ppmv.

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Sea level

Changes in sea level will occur as a consequence of climatic warming through the thermal expansion of sea water and melting of ice. The estimates for the global rise in sea level by the 2050s due to climate change range from about 10 to 50 cm, with a mid-range estimate of about 20 cm. The UK regional change in sea level is quite similar to the global average, but natural subsidence would add about 9 cm to the 2050s estimates for south eastern UK. Natural rebound of land in the north would subtract about 12 cm from the global rise in sea level. A sea level rise will affect the frequency of damaging surges of water along the coast during storms.

Seasonal temperatures

Changes in the mean annual temperature over the UK are likely to follow the global average closely. However, UK winters will warm a little faster and summers a little slower than the global average. By the 2050s, for example, the Hadley model for the UK suggests summer temperatures between 1 and 1.5°C warmer than at present and winter temperatures warmer by between 1.5 and 2.5°C. Assuming no change in inter-annual variability, the following rises in mean summer temperatures might be expected:

- by 2010: a temperature increase of 0.5°C, increasing the likelihood of a '1995-type' hot summer from about a 1 in 100 year event to 1 year in every 25;
- by 2030: a temperature increase of 1°C, with a '1995' summer every ten years;
- by 2050: a 1.5°C temperature rise, with a '1995' summer occurring one year in three.

Seasonal precipitation

Simulated changes in mean seasonal precipitation over the UK are relatively modest in the Hadley model simulations. By the 2050s, for example, winter precipitation may increase by about 0.5 mm/day (15-25%) over much of the UK. In summer, the precipitation changes are smaller, amounting to less than 5% of summer precipitation totals, distributed as a slight wetting in the south and slight drying in the north (Figure 1.3). These changes in summer precipitation are mostly indistinguishable from the natural variability of UK precipitation (Table 1.1).

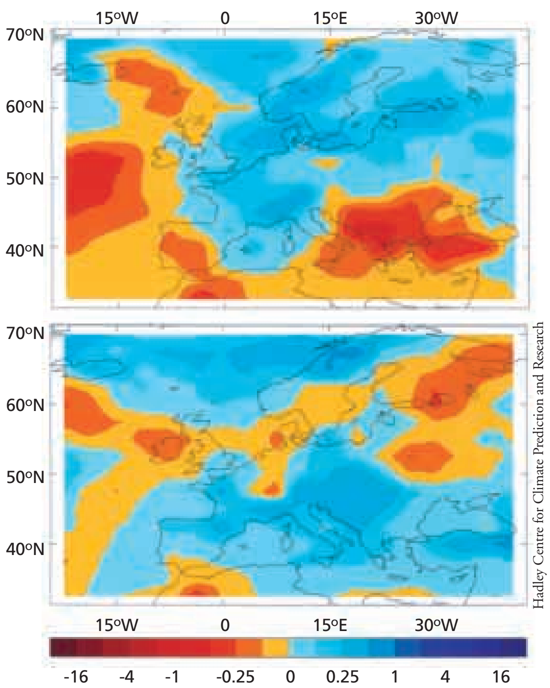

Figure 1.3: Two scenarios of summer precipitation (difference from present day to 2030-50, mm/day). The top shows the effect of greenhouse gases only. The bottom combines the effects of greenhouse gases and sulphate aerosols. The patterns are quite different for these two scenarios, highlighting the uncertainty in projections of precipitation change. Source: HADCM2 model from the Hadley Centre, Bracknell.

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Scenario	Summer	Winter
Natural variability	+6.5%	+5.5%
2050s	+1%	+21%
2050s, with aerosols	-1%	+5%

Table 1.1: Mean seasonal precipitation changes for the UK by the 2050s from the Hadley Centre experiments (HADCM2 model) with respect to 1961-90. The estimate of natural variability (that is without climate change) is based on the control simulation.

Irrespective of whether total precipitation increases or decreases, a greater proportion of precipitation in the future is likely to fall in more intense events, especially in winter.

Storminess

Mean daily windspeeds may be expected to increase in the future in both summer and winter seasons, with perhaps greater increases over northern UK.

1.4
AGRICULTURAL CONTRIBUTION TO CLIMATE CHANGE

The total global warming potential of UK emissions is made up of the following: CO_2 80%, methane 11%, nitrous oxide 7%, industrial gases 2%. Agriculture causes 8%1 of these total losses and, in particular, is a significant source of two of the major non-CO_2 greenhouse gases: methane and nitrous oxide. The sources and sinks of greenhouse gases from agriculture are discussed further in this section.

		Contribution to global warming			
Gas	Atmospheric concentration (ppmv)	Lifetime (years)	Relative impact	Contribution (%)	Annual emissions 1995 ($x10^8$ tonnes)
CO_2	353	50-230	1	60	79 (carbon)
Methane	1.7	10	25	15	5.25
Nitrous oxide	0.31	150	200	5	0.133 (nitrogen)
Industrial compounds	<0.0001	65-130	12-15000	12	0.00577

Table 1.2: Greenhouse gas contributions to climate change.
Notes: Industrial compounds are for CFC-11 and CFC-12 (others are also important). Sources: Rodhe (1990); global emissions are for the IS92a scenario from the Model for the Assessment of Greenhouse-gas Induced Climate Change, University of East Anglia.

Carbon dioxide

CO_2 is the most globally abundant greenhouse gas and makes the largest contribution to global warming (Table 1.2). The situation is the same for the UK. Major UK sources of CO_2 are burning fossil fuel for energy, transport and industry. Fossil fuel and lime use on farms accounts for less than 1% of UK emissions of CO_2 in 1990, though the sector also contributes to CO_2 emissions through soil cultivation and indirectly through demand for manufactured fertiliser and transport of agricultural goods.

Agriculture makes only a small contribution to the carbon cycle through natural processes such as decomposition of organic materials and respiration from living organisms. More importantly, CO_2 is the principal source of carbon for plants and thus photosynthesis is a major sink within the carbon cycle. Nevertheless, the removal of CO_2 from the atmosphere by growing plants and its subsequent release after they are harvested is generally balanced over an annual cycle.

There is approximately twice as much carbon stored as dead organic matter in soil worldwide as there is in 'live' forests. Within the UK, much carbon is held in soils as soil organic matter, largely in upland peats and to a lesser extent in established grassland soils. Carbon can be lost from soils when organic matter decomposes and these losses could be exacerbated by climate change. The process is complex however, depending on the amount of carbon returned through crop residues as well as soil temperature and moisture.

Changes in land use may alter the rate at which carbon accumulates or is released. For instance, drainage and tillage of upland peat and conversion of permanent grassland into arable crops would release more carbon. Within the

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UK, the effects of land use are currently small, but not insignificant, compared with emissions from fossil fuels and industry, at around 5% of total UK emissions of CO_2.

Lastly, agriculture could help increase carbon accumulation through afforestation and producing energy crops to replace fossil fuels.

Box 1.3
Carbon

The **carbon cycle** is the movement of carbon between the atmosphere, terrestrial biosphere, freshwater systems, oceans, sediments and fossil fuel deposits via interconnected pathways of exchange. **Carbon sinks** are reservoirs that absorb or take up carbon. **Carbon sources** are reservoirs that release carbon.

Methane

In contrast to CO_2 , nearly a third of methane emissions in 1990 in the UK were from agriculture. The proportion has increased to nearly 40% in 1998, mainly as a result of reduced emissions from landfill. Most agricultural methane (90%) is from ruminant livestock production, caused by the digestive process in ruminant guts. A mature dairy cow can release over 100 kg of methane each year.

As well as direct emissions from livestock, there are also smaller losses from dung deposited by grazing animals and from stored and applied farm wastes, dirty water and silage effluent.

For a typical dairy farm of 180 ha, the net flux of methane is 316 kg per hectare per year, dominated by direct output from cattle (Figure 1.4). Calculations for a mixed farm show greater removal of methane from the atmosphere by the other components of the farm. Cattle account for 75% of UK methane emissions from livestock.

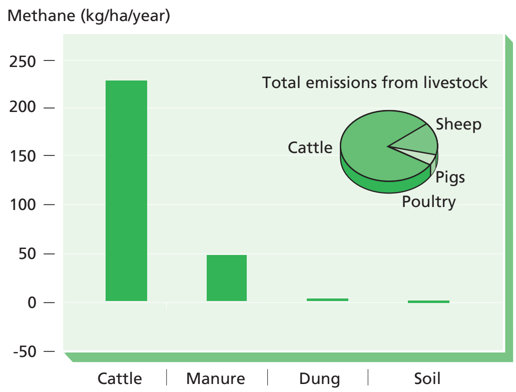

Figure 1.4: Methane emissions from a typical dairy farm (columns) and for the UK (pie). Source: Jarvis and Moss (1994) and Sneath *et al.* (1997).

Any reduction in ruminant livestock numbers will reduce methane emissions. Increasing productivity per animal (through improved dietary regimes, improved health and welfare and maximising genetic potential) is likely to be the most practical way to reduce emissions. Other possibilities might include changes to animal diet and to the rumen microbial population (the protozoan complement is particularly important in generating methane). There may also be some scope for reducing emissions from manure and slurries by developing alternative storage and handling procedures. Utilisation of methane emissions from farm wastes as an energy source (for example through anaerobic digestion) is sometimes proposed as a means of reducing greenhouse gas emissions, although it tends not to be economically viable in most situations.

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Nitrous oxide

Agriculture caused nearly half of UK emissions of nitrous oxide in 1990. This proportion is likely to increase to around 70% by 2000, mainly due to greatly reduced nitrous oxide emissions from industrial processes. Fertilisers and animal wastes are responsible, in equal measure, for 90% of this figure, with the remainder of emissions coming from crop residue incorporation, biological nitrogen fixation and the cultivation of organic soils (see Figure 1.5).

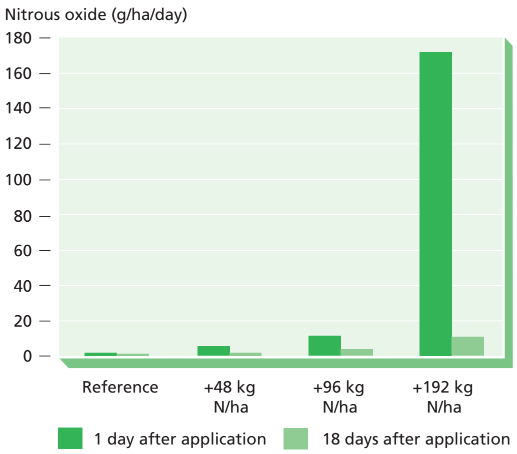

Figure 1.5: Nitrous oxide releases after application of fertiliser. Source: Harrison *et al.* (1995).

Non-agricultural sources include industrial processes, power stations and road transport. However these are set to decline and agriculture will be responsible for an increasing proportion of the UK's nitrous oxide losses.

Natural processes in the soil generate nitrous oxide but these are enhanced by the addition of nitrogen as fertiliser or animal excreta. The production of nitrous oxide in soils is highly variable depending on very local soil conditions of moisture content, aerobicity, and availability of reactive nitrogen and carbon. On grazed pastures the variability is further enhanced by the highly uneven spatial and temporal distribution of nitrogen in dung and urine from livestock. Figure 1.6 shows the variation in emissions with season and soil type.

Research is underway to examine agricultural emissions and assess ways of reducing them. Options to minimise nitrous oxide release include:

- reduce farm nitrogen inputs and increase their efficiency; for example, by taking better account of the nutrients in manures and using them to substitute for inorganic fertilisers;
- focus timing of fertiliser application in relation to soil conditions and crop demand, with better use of weather and yield prediction;
- improve placement of fertiliser.

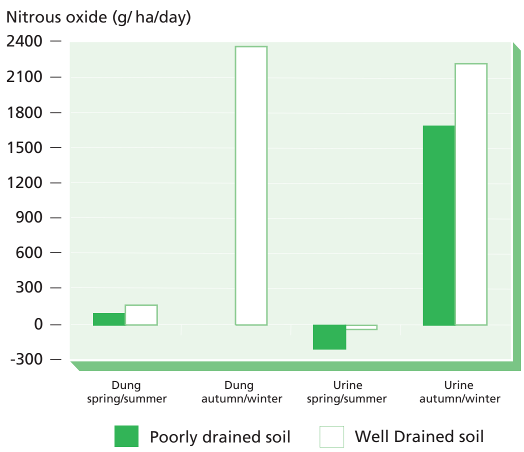

Figure 1.6: Nitrous oxide fluxes from excreta. Source: Allen *et al.* (1996).

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Box 1.4
Ozone depletion and UV-B radiation

The depletion of stratospheric ozone is related to the climate change issue and has received considerable publicity. But its effects are related to changes in solar radiation, rather than to changes in weather. The Montreal Protocol on Substances that Deplete the Ozone Layer, first signed in 1987 and now ratified by 160 countries, has been successful in limiting ozone depletion by controlling the production and consumption of ozone - depleting substances. The amount of CFCs and other ozone - depleting substances being released into the atmosphere has now substantially decreased. Scientists predict that if the controls that have now been agreed under the Protocol are adhered to by all countries, the ozone layer is expected to recover to pre-ozone hole levels by the second half of the next century.

Ozone is a major element in the 'global sunscreen' that filters out components of sunlight that would be lethal to living processes if they penetrated to the Earth's surface. Natural sunlight is a mixture of many different wavelengths of light. Passing sunlight through a prism splits it into its component wavelengths, visible as the different colours of the rainbow (Figure 1.7). Beyond the range of the human eye, the spectrum continues to shorter wavelengths: this is ultraviolet light or ultraviolet radiation. The longest wavelengths of ultraviolet radiation are known as ultraviolet-A (UV-A) radiation. UV-A tans human skin, but is less harmful and is not affected by ozone depletion. UV-B consists of the shortest wavelengths of sunlight to reach the Earth's surface and its level increases as the ozone layer thins. UV-B causes sunburn and is implicated in the development of some skin cancers.

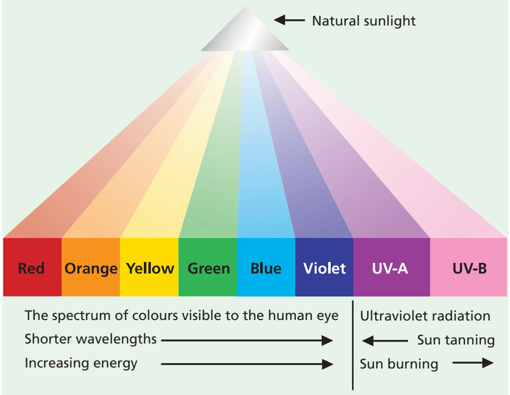

Figure 1.7: The spectrum from visible light to ultraviolet radiation at shorter wavelengths.

The amount of UV-B radiation reaching the Earth's surface, like visible light, is highly variable, affected by season, time of day, cloud cover and other weather conditions. Even with quite marked ozone loss, UV-B levels for much of the year would be lower than their current mid-summer maximum. However, given average UV-B levels, each 1% decrease in ozone is expected to result in roughly a 1-2% increase in the UV-B radiation that affects biological processes. Several scientific studies show how changing UV-B might affect crops, but there are large variation in responses (Table 1.3). Some crops, such as wheat, appear to be consistently insensitive to even quite intense UV-B treatments. In contrast, barley is rather more sensitive to UV-B effects. A number of broad-leaved crops are also sensitive to the effects of UV-B, with legumes such as peas and beans being particularly vulnerable. However, the range of plants that have been adequately studied remains limited to a few major arable crops. The effects of increased UV-B on forage crops and grasses, horticultural fruit and vegetables, and especially long-lived woody species, are poorly defined.

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Potentially sensitive	Likely to be tolerant
Barley	Wheat
Peas	Forage grasses
Beans	Certain vegetables (onion, parsnip, celery)
Oilseed rape	
Oats	
Potatoes	
Sugarbeet	
Rye	
Many vegetable crops	

Table 1.3: Possible vulnerability of UK crops to UV-B radiation.

Classification is mainly based on glasshouse and growth room studies which may overestimate responses. Greatest confidence can be placed in the assessments for wheat, barley and peas where field data are available.

The consensus from the great majority of recent field experiments is that increased UV-B alone will not cause dramatic damage to crop plants. Given our current understanding, there is little likelihood that increased UV-B will cause significant economic losses in UK crops so long as controls on ozone-depleting substances are adequately implemented worldwide.

2. UK Farming in Context

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Agriculture dominates the UK landscape: it occupies over 75% of the land area and contributes 1.4% to Gross Domestic Product. The agricultural industry has adapted in the past; future success will stem from its ability to adapt to local, national and global changes in climate, policy, technology and the economy. This chapter reviews the historical context and the role of global markets, as a background to the impact of climate change on UK agriculture.

The Second World War brought to an end a century-long policy of non-intervention in farming in the UK. The 1947 Agriculture Act introduced guaranteed prices for farm products, with deficiency payments funded by the taxpayer. On joining the European Community, support for agriculture continued under the Common Agricultural Policy (CAP). The CAP was extremely successful in boosting European agricultural output. However, by the 1980s, large surpluses of most indigenous products were produced in the Community, and quotas and set-aside regimes were needed to control production.

2.1
HISTORICAL CHANGES

UK agriculture has embraced new technology and practice at an unprecedented rate since the war (Figure 2.1). This has mainly been in the form of increased mechanisation, increased use of inorganic fertilisers and agrochemicals, and continuous improvement of plant varieties and livestock breeds. We can expect this trend to continue.

Wheat provides a good example of the effects on yields (Figure 2.2). The five-year average UK wheat yields more than doubled from 3 tonnes per/ha (t/ha) in 1950-54, to 7.5 t/ha in 1992-96. Nitrogen applications increased between four and tenfold between the 1940s and 1990s - from less than 20 t/ha to almost 200 t/ha for winter wheat.

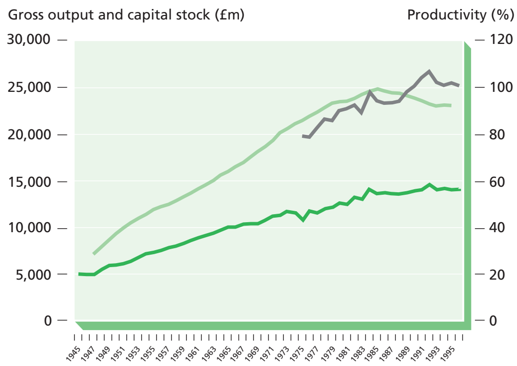

Figure 2.1: Gross output (dark green), gross capital stock (light green) and productivity (grey) of agriculture (output per unit of inputs; right axis). Gross output includes crop and livestock production and subsidies, and is given at 1990 prices. Gross capital stock indicates the uptake of new and improved forms of machines, vehicles and buildings, and is given at 1985 prices. The productivity is calculated as the gross output per unit of all inputs relative to 1990.

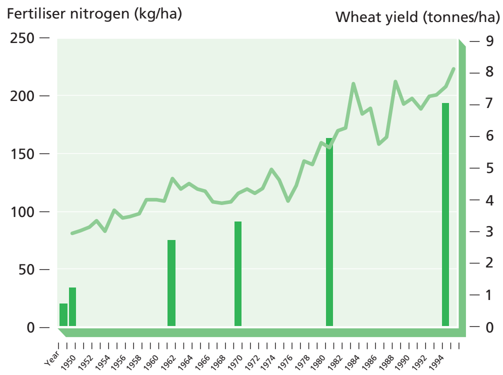

Figure 2.2: Fertilizer nitrogen use in England and Wales (bars) and average UK yields for winter wheat (line).

The structure and economics of farming have changed in conjunction with new agricultural policies and improved technology. Between 1945 and 1995 the number of holdings in the UK halved and the average size, in terms of hectares of crops and grass, doubled. Meanwhile, the long-term trend since the last century towards owner-occupation of farms has continued: in England and Wales the proportion of holdings owned by their occupiers increased from 44% in 1950 to 67% in 1995.

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The pattern of land use on farms has changed over the last few decades. The total area of rough grazing in the UK has declined since 1945, permanent (improved) grassland has increased, and the area in short-term grass ley has declined as the profitability of other enterprises has increased relative to grazing livestock. The total cropped area declined between 1945 and 1970 but has since increased.

Total areas of wheat and barley are now approximately double what they were in the late 1940s (Figure 2.3). Oats and mixed corn, both important feed grains just after the war, now occupy less than a tenth of the area recorded in 1950. The area of potatoes has declined by 70% over a similar time-scale. A new crop in the UK since the late 1960s is oilseed rape, now accounting for around 7% of the total cropped area. The practice of leaving arable land uncropped for a period as bare fallow has declined markedly in the post-war period, but set-aside policy since the late 1980s has taken large areas out of production.

Grass-based livestock rearing has seen less dramatic change over the last 50 years than cropping. While total cattle numbers grew slowly to 12 million in 1990, the number of sheep and lambs increased by nearly 50% during the 1980s. Intensive livestock production expanded rapidly during the 1950s and 1960s. For example, technological changes in management led to poultry numbers roughly doubling over the period to 1970.

Agricultural production has become more intense, but with less labour. Over the past 20 years, the average area of cereals on farms has increased from 32 to 46 hectares, yet the average size of holding has hardly risen. Agricultural workers had fallen to 243,000 in 1995 from 430,000 in 1970 and nearly a million at the end of the war.

While these changes in the size and structure of the industry were occurring, the volume of production increased. Gross output of UK agriculture rose from £4.9 billion in 1945 to an estimated £14 billion in 1996 (Figure 2.1). Gross output per unit of all inputs, available on a comparable basis since 1975, shows that total productivity has increased on average by just over 1% per annum.

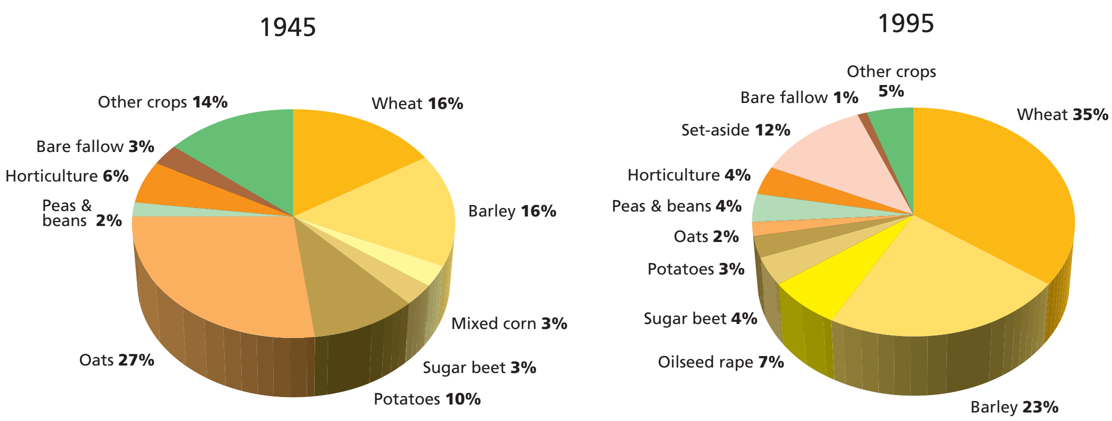

Figure 2.3: UK agricultural cropped area in 1945 and 1995.

UK Farming in Context

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2.2 GLOBAL CONTEXT: PRODUCTION AND PRICES

The UK will not experience the impacts of climate change in isolation. Effects on crops and livestock in other countries will alter agricultural production worldwide. Production changes will affect the prices commanded by different farm products, and their profitability and relative competitiveness. The crops and animals that the UK produces in the future will, therefore, depend on both world prices for agricultural products (affected by global climate change) and local production potential (affected by local climate).

Models predict that climate change will have quite different effects on agricultural yields in various parts of the world. At the higher latitudes (beyond 50°N and 50°S), warmer temperatures are predicted to lengthen and increase the intensity of the growing season. Yields are likely to increase in these regions as long as there are no major changes in rainfall. In contrast, in tropical and equatorial regions warmer temperatures may exacerbate already quite frequent water and heat stress on plants due to higher rates of evaporation. Crop and livestock yields may decrease in these areas. The unequal distribution of losses and gains in yields would have a major effect on where food is produced, how much is traded and relative prices.

Even without climate change, models predict large changes in food demand and production:

- population doubles from 5 to 10 billion by the middle of the next century;
- economic wealth increases dramatically and per capita income rises;
- farm technology improves considerably;
- barriers to free trade are reduced by 50% with enactment of present global agreements.

In the absence of climate change, world cereal production is predicted to increase by about 80% from 1800 million tonnes in 1990 to about 3300 million tonnes by the middle of the next century ('a' in Figure 2.4).

The projected large increase in global production is reduced by 5-15% when climate change is taken into account ('b' in Figure 2.4).

The prospective impacts of climate change will lead to adaptive responses by farmers and in the agricultural system as a whole. Two levels of adaptation were considered: farm level, low cost ('c' in Figure 2.4) such as changing planting dates and cultivars and regional, higher cost ('d' in Figure 2.4) which includes irrigation and land use change. When adaptive responses are considered, the reduction in global output decreases to between 2% and 5% of the reference case ('c' and 'd' in Figure 2.4).

Without climate change, future food prices in Europe are most likely to fall in real terms due to increasing yields, the global expansion of the farmed area and trade liberalisation (Table 2.1). This is likely to slow, but not reverse, the trend to lower commodity prices (Table 2.1).

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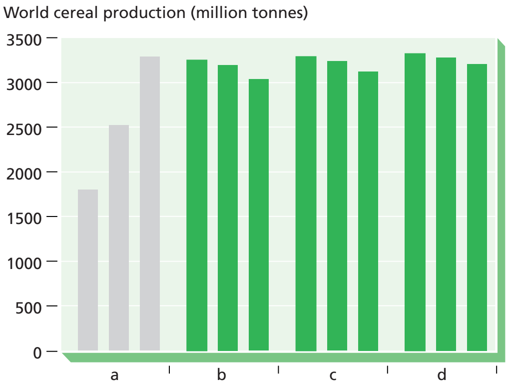

Figure 2.4: World cereal production (total of wheat, rice, maize, millet and sorghum) projected for 2060 from three climate models and for two levels of adaptation. (a) No climate change; (b) climate change only; (c) climate change with deployment of all currently known technology; (d) climate change with massive inter-state water transfers and new genotype development. Source: Rosenweig *et al.* (1993).

This suggests that the profitability of grain production in the UK under a warmer climate might be reduced. In contrast, meat production might benefit as prices are generally expected to remain higher (Table 2.1) and to be driven even higher by climate change in Europe (Table 2.2). Feed prices could substantially decrease due to climate change because soya yields are estimated to increase worldwide by over 10% as a result of the beneficial effects of higher levels of CO_2 in the atmosphere. These price changes are determined by the world food market (through global supply and demand) and will be felt by farmers in the UK.

	Prices			Demand		
Commodity	**2010**	**2030**	**2050**	**2010**	**2030**	**2050**
Wheat	83	80	80	106	104	98
Rice	86	77	72	115	120	119
Coarse grains	84	80	74	123	131	135
Bovine, ovine	101	93	85	102	100	95
Dairy	94	90	82	104	102	96
Pork, poultry, eggs	90	83	77	114	121	122
Protein feed	103	106	110	106	105	97
Other food	85	77	71	106	106	101
Non-food	79	69	63	100	96	88

Source: Parry *et at.* (1997)

Table 2.1: Estimates of future prices and demand for agricultural products in Europe without the effects of climate change, 2010 to 2050 (1990 = 100).

These modelling studies present only one scenario of the effects of global climate change on agricultural prices in the UK. However, it is certain that the impacts of climate change on UK production will not only be influenced by the effects of local changes in climate on crop and livestock yields, but also by the effects of global changes in climate on agriculture worldwide and the knock-on effects on UK agricultural prices.

	Prices			Demand		
Commodity	**2010**	**2030**	**2050**	**2010**	**2030**	**2050**
Wheat	88	101	101	101	98	96
Rice	114	126	136	101	100	101
Coarse grains	90	99	95	100	101	103
Bovine, ovine	99	102	103	99	100	99
Dairy	99	102	103	100	100	101
Pork, poultry, eggs	97	100	99	101	100	100
Protein feed	78	86	81	112	115	120
Other food	92	103	102	100	100	100
Non-food	89	103	102	101	100	100

Source: Parry *et at.* (1996).

Table 2.2: Estimated changes in prices and demand for agricultural products in Europe due to climate change. The index is relative to the future without climate change as shown in Table 2.1 (=100).

2.3 THE FUTURE

It is important to recognise that climate change is only one of many factors that will shape the future of UK agriculture. It is impossible to predict all the other changes that could have an impact in the future. We know that the next round of the World Trade Organization (WTO) negotiations and further reforms of the Common Agricultural Policy could have significant effects over the next few years. Equally, advances in technology and continuing consumer pressures are likely to have a large effect on the way the industry develops.

3. Impact of Climate Change on Crop and Soil Processes

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Chapter 1 outlined the relative confidence in projected changes in CO_2 concentrations, temperature and precipitation. This chapter discusses the impacts of climate change on crop and soil processes, and on consequences for land and water use.

3.1 CROP PROCESSES

The relative confidence in the elements of climate change implies different effects on agriculture (Table 3.1). Increased CO_2 concentrations are mostly beneficial, whereas temperature and precipitation effects can be both beneficial and detrimental. Possible changes in storminess and the variability of climate are highly uncertain but could have significant effects on the risk of crop losses. A rise in sea level would affect some areas through loss of land or salinisation of groundwater (see Box 3.1).

Climate	Confidence element	Effects on agriculture
CO_2	Very high	Beneficial effects for most UK crops: increased rate of photosynthesis, reduced water use.
Sea level rise	Very high	Loss of land, salinisation of groundwater.
Temperature	High	Accelerated growth, shorter and earlier growing season, expand suitability northward and to higher elevations, risk of adverse temperatures, reduced grain yield through shorter season, higher potential evapotranspiration.
Precipitation	Low	Effects depend on extent of precipitation change for drought risk, soil workability, water logging, supply of irrigation water and transpiration.
Storminess	Very low	Risk of lodging, soil erosion, reduced infiltration of rainfall.
Variability	Very low	Potential changes in the risk of damaging events (heat waves, frost, drought, floods) affecting crop yields and quality, timing of farming operations.

Table 3.1. Confidence in the major effects of climate change on agriculture.

Elevated CO_2 concentration

The effect of increased CO_2 concentrations alone on plants is to increase the rate of photosynthesis and reduce the amount of water required per unit of biomass and yield (see Box 3.1 for definitions of the processes relating to CO_2 enrichment

The rate of photosynthesis is 'driven' by light intensity and the rate of CO_2 supply. Light intensity changes with season, time of day and cloud cover; CO_2 changes with the concentration in the atmosphere, the resistance of the air next to the leaf surface and the pores in the leaf surface (stomata). In dim light the rate of photosynthesis is limited by light energy but in bright conditions CO_2 supply is limiting. When both light and CO_2 are in abundance, the intrinsic rates of the biochemical processes (which depend on temperature) limit the rate of photosynthesis.

Increased photosynthesis provides extra sugars and other products for growth and, as the leaf area increases, light interception may be enhanced. If water, fertilisers and control of pests, diseases and weeds are adequate, the rate of increase in production in most UK arable crops will be about 0.1% per year at current rates of CO_2 increase, so that in the absence of any

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accompanying increase in temperature, by 2080 a 20-30% increase in production would be possible. These potential effects of CO_2 enrichment are unlikely always to be fully realised.

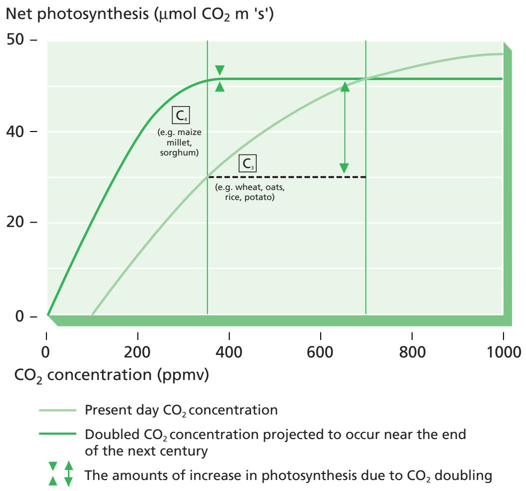

Figure 3.1: Responses of net photosynthesis of C3 and C4 plants to increasing concentrations of carbon dioxide. Source: adapted from Taiz and Zeiger (1991).

Box 3.1
Plant physiology and processes

Photosynthesis is the process that plants use to manufacture carbohydrates from carbon dioxide and water, using part of the spectrum of sunlight as the energy source. Oxygen and water vapour are released by the process. Photosynthesis depends on favourable temperatures and moisture. At night, plants use up energy, in a process called respiration. Increased levels of carbon dioxide can increase net photosynthesis (the difference between photosynthesis and respiration) in many plants and use the extra carbonhydrates produced for increased growth. This effect is called **carbon dioxide fertilisation**.

The CO_2 fertilisation effect depends on the type of plant. In the first step of photosynthesis, **C3 plants** (nearly all UK crops such as wheat, oats, barley and potatoes as well as rice and soybean) make a compound containing three carbon atoms. Using a slightly different mechanism, **C4 plants** (a smaller number of crop plants such as maize, millet and sorghum) produce a four-carbon compound. These different reactions in the plant are the reason why C3 and C4 plants respond differently to increased concentrations of CO_2 (Figure 3.1).

Minute pores in leaves and stems govern the exchange of gases (carbon dioxide, oxygen and water vapour) between the plant and the atmosphere. The pores, called **stomata**, close when water loss through transpiration is too high and in response to drought. Stomatal closure reduces CO_2, uptake as well as water loss, thus decreasing the rate of photosynthesis. However, in high CO_2, the difference in the CO_2 concentration in the leaf and in the atmosphere is greater than at present, so CO_2 can pass through partially closed stomata at a rate similar to that under conditions of lower CO_2 and open stomata. The net result is improved water-use efficiency, most notably in C3 plants.

Water-use efficiency is a measure of the amount of water used by plants per unit of plant material produced. The term can be applied at different levels. At the leaf level, it refers to the rate of CO_2 uptake divided by the rate of water use. At the plant level, it is commonly measured as the amount of dry matter (or yield) divided by the amount of water used (for example, kg grain yield/mm water transpired). At the ecosystem level, evaporation from the soil, for example during the fallow season, is included. The uncertainties are greatest at the ecosystem level, where it is difficult to estimate the combined effect of different crops, grass, shrubs, trees and bare soil.

Impact of Climate Change on Crop and Soil Processes

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Warmer temperatures

Increased temperatures will have profound effects on crop development. The impacts depend on relative warming in different growth stages: seed germination, seedling emergence, flower initiation, flower development, pollination, ripening, maturity, leaf production, leaf expansion, leaf area duration, vernalization and dormancy.

Developments will be earlier if warmer winters and springs occur, and more growth may occur during the part of the growing season (see Box 3.2) with longer days. Most crops will respond in this way except those where low temperatures are necessary for vernalization. Autumn-sown crops may suffer due to very warm seed-beds but later sowing will avoid this. Earlier growth will be particularly advantageous for herbage production and early vegetables.

Box 3.2
Growing season

The growing season of **determinate** crops, such as winter wheat, is governed by the warmth of the season. Warmer seasons lead to shorter development stages and total growing periods. In contrast, **indeterminate** crops, such as sugar beet, continue to produce leaves and other organs for as long as the temperature remains suitable. Yields increase with temperature rises. Some crops are also sensitive to **photoperiod**, the length of daylight. Change in photoperiod during the season can trigger certain developmental phases.

Crops could be produced further north and at higher altitudes as the thermal limit of cultivation expands. Conditions in the southern UK may become more suitable for crops common in continental Europe, such as grain maize and sunflower.

The beneficial effects of warming may be tempered by adverse consequences. Increased development rates may be detrimental for some crops. Determinate crops such as wheat and barley that depend on accumulated heat to trigger each developmental stage will have shorter development phases. The periods of grain filling and ripening may be too short to produce satisfactory yields. Early maturity induces woodiness in horticultural crops. To overcome this, selection of new cultivars or management practices may be required, for example by cutting herbage to keep crops in a vegetative condition. Indeterminate crops such as sugar beet will be able to take advantage of the extra warmth by growing faster.

Beyond an upper thermal limit, the crop may be damaged. Hotter summers with short periods of extreme temperature may increase the risk of damage to crops, for example in the formation and release of pollen. Pollination in many crops, including wheat, is inhibited by temperatures only a few degrees above average. Earlier growth may make the crop more susceptible to late frosts that cause considerable damage to juvenile plants. Differences between crops and varieties in their sensitivity to temperature are considerable, so it should be possible to overcome these problems by breeding new crop varieties.

Respiration uses some 50% of the energy produced by photosynthesis, so a relatively small increase in temperature, and thus respiration rate, may have a large impact on assimilates available for growth. Inadequate assimilate is probably the most likely reason for lower yields of wheat in southern England (around 7 t/ha recently)

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compared with Scotland (about 8 t/ha) where temperatures are lower and summer days are longer. In the Paris basin, wheat yields are lower, at around 6 t/ha.

Warming will benefit agriculture in areas where current temperatures do not approach the optimum. For example, maize will be able to germinate in the UK before the period of maximum radiation is reached in June, encouraging the spread of maize towards the north. Where the optimum temperature is currently close to the long-term average, further warming may have adverse effects. One response would be to shift cultivation northwards closer to the new range of optimum temperatures.

Precipitation and water balance

Even small changes in precipitation will have profound consequences for plant production. Increased precipitation in winter may stimulate diseases, requiring greater use of various control methods. On wet, poorly drained land, waterlogging could increase with consequences for soil workability (see section 3.3). Decreased spring and summer rainfall would have serious implications, decreasing crop water supply, especially on light soils, increasing moisture stress and reducing growth. The impact on horticultural crops could be severe.
Demand for irrigation would probably increase (see section 3.3).

With all other factors held constant, warmer temperatures will increase evapotranspiration from soils and crops. Simple calculations (using a modified Penman equation and assuming no changes in water-use efficiency) suggest that summer potential evapotranspiration will increase by about 5% by the 2050s under the Hadley Centre HADCM2 scenario over the southern UK and by about 3% over the northern UK. If combined with a 6-7% decrease in precipitation, as already experienced over England and Wales, the consequences could be substantial for herbage production, horticultural crops and even cereals on light land. Other factors, however, will not remain constant in the future and changes in CO_2 concentration, radiation, vapour pressure and windspeed will all affect potential evapotranspiration rates.

As noted above, elevated CO_2 concentrations increase stomatal resistance, which decreases transpiration. Decreased transpiration, however, results in warmer leaves and air in the crop stand, which accelerates water loss. Experiments show that elevated CO_2 does decrease transpiration: a 15-30% reduction for a doubling of CO_2 concentrations is common. Water-use efficiency increases substantially (perhaps up to 50%) with a doubling of CO_2; production increases and transpiration decreases.

Related to precipitation, changes in cloud cover and solar radiation would also affect crop growth and yield. Increased sunlight would increase crop growth, but also increase water use. Elevated CO_2 will allow crops to take greater advantage of the additional solar energy. Or conversely, elevated CO_2 may reduce the impact of greater cloud cover and less radiation.

Over the next few decades:

- Agriculture in the UK will benefit from CO_2 and warmer temperatures, up to a point and as long as precipitation does not change significantly.

- The extent of the impacts on yield and yield quality varies between crops, cultivars and even plants. There is likely to be a need to develop new cultivars to cope with climate change.

Impact of Climate Change on Crop and Soil Processes

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- Predictions of effects on individual crops are hampered by uncertain scenarios of climate change and the lack of experiments on the interactions of extreme temperatures, CO_2 enrichment and water stress.

3.2 SOIL PROCESSES

Climate change will modify key soil processes that underpin crop growth and management. This could have profound implications for agriculture worldwide. For example, land degradation and loss of soil productivity could become a real danger in some areas.

Soil processes are influenced directly by temperature, precipitation and atmospheric CO_2 changes, particularly as these affect the soil ecology and organic matter. This in turn affects soil structure, water regime and plant growth. In addition, precipitation intensity and amounts could alter erosion rates.

The indirect effects of changing land use and agricultural systems can have great effects on soils, more so than the direct effects of climate change on soil processes.

Soil ecology and organic matter

Soil organic matter ranges from undecayed plant and animal remains, through ephemeral products of decomposition to more or less unstructured organic material, often termed humus. Soil organic matter affects nutrient cycling as well as the physical properties of soils, primarily by modifying the size and stability of aggregates and their surface adsorption and desorption characteristics. The rate of organic matter decomposition is related to temperature and the activity of soil organisms. Increases in temperature will increase the activity of soil organisms, resulting in significant release of CO_2 as a consequence of decomposition (see Figure 3.2). It is likely that equilibrium soil organic matter levels will be lower with increased average temperature. Soil organisms, however, have relatively broad temperature optima, so small increases in temperature are unlikely to have a large influence on the distribution of soil organisms. However, changes in litter supply, fine roots and soil moisture resulting from CO_2 effects are likely to influence soil organisms. Furthermore, shifts in the abundance of pathogens and symbiotic organisms within the soil are likely to result from changes in crops grown or land cover.

Changes in soil ecology and organic matter in response to climate change can have far-reaching implications for agriculture by modifying, for example:

- soil porosity and water availability for crop growth;
- surface strength of soils and the potential for soil erosion and landslips and the implications for tillage;
- rate of movement of water and organic and inorganic chemicals through the unsaturated zone of the soil profile (leaching);
- capacity of soils to store and cycle carbon and nitrogen, as well as the micronutrients required for crop growth;
- populations of soil fauna and microflora present in the crop root zone which contribute to both the composition of soil organic matter and its turnover in the soil;
- quantity of soil microbia and their capacity to generate or immobilise CO_2, methane and nitrous oxide.

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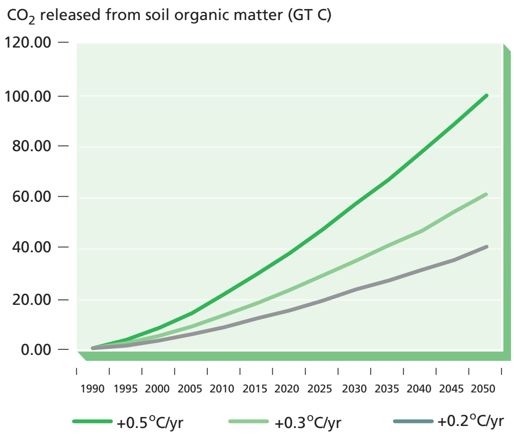

Figure 3.2: CO_2 release from soil organic matter over time, under different climate change scenarios.

Soil structure

Soil structure influences the movement of water, nutrients, pesticides and other additives within the root zone and into plants. Structure is influenced by the inorganic and organic constituents of the soil matrix, by tillage operations and by the physical processes of shrink-swell and freeze-thaw.

Soils with high clay contents have the potential to shrink when they are dry and swell as they become wet again, resulting in the formation of large cracks and fissures. Drier climatic conditions would increase the frequency and size of crack formation in UK soils, which currently do not reach their full shrinkage potential, as well as producing hard soil surfaces and cloddy seed-bed conditions. Such properties make these soils very difficult to manage for cultivation. A further consequence of crack formation is the more rapid and direct movement of water and solutes from the soil surface to permeable substrata or drainage installations through by-pass flow. The direct movement of water in this way decreases the filtering capacity of soil and increases the possibility of nutrient and pesticide losses and pollution of groundwater and surface water. Where animal manures or sewage sludge are applied to land, there will be a greater risk of organic contaminants and micro-organisms reaching aquifers.

Soil water content

The soil is an enormous reservoir for water. Soil water content is determined by the balance of infiltration, drainage and evaporation from the soil surface and from the plant and ground cover (transpiration). Changes in temperature and atmospheric CO_2 concentrations will also affect soil water content through their influence on evapotranspiration and plant water use.

Soil workability, trafficability and poaching risk

The soil water content has a substantial influence on the distribution and management of arable crops in the UK. *Workability* refers to soil conditions suitable for tillage, for example in the preparation of seed-beds. *Trafficability* is the accessibility of land during crop husbandry. Workability requires the soil to be neither too wet (so avoiding yield losses associated with compaction or smearing) nor too dry in which the production of a fine tilth can be difficult. Currently wet areas of the UK, especially those with heavy soils, would benefit from an increase in the accessibility period for machinery, as soils become drier. However, any benefits for workability of increasing temperatures will be offset if rainfall also increases: a 10% increase in rainfall in the UK offsets a 2°C rise in temperature. Reduced rainfall arising from climate change will result in large improvements in soil workability conditions in the currently wetter areas of the UK.

Impact of Climate Change on Crop and Soil Processes

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In grassland systems, the tendency for poaching by grazing livestock is analogous to soil workability for machinery. Changes in the period of the year when soil conditions are sufficiently dry to avoid poaching, as a result of climate change, would change the potential geographical distribution of intensively managed agricultural grassland in England and Wales. More intensive management of currently wet upland grazing areas is a likely consequence of climate change.

Land degradation

The impact of climate change on soil erosion within the UK will be strongly regionalised, depending on the frequency and intensity of precipitation, windspeed and direction, soil structure, land cover, aspect and slope. For example, in upland grazed areas, higher temperatures will extend the duration of the growing season so that decreased erosion rates would result from better soil cover. The stability of upland topsoils will also be enhanced by fewer frosts as a result of higher temperatures. More frequent, heavier precipitation before winter-sown cereals establish a full ground-covering canopy could lead to large increases in soil erosion in some lowland situations. Earlier harvest could also expose soils to late summer and early autumn storms and thus increase erosion.

In well-drained, structurally stable soils, increased amounts and intensity of precipitation will result in a greater potential for leaching. This could increase soil acidification through the depletion of basic cations (e.g. upland podzols), although acidification will probably only become evident after buffering pools are exhausted.

Peats are among the most fragile agricultural soils in the world. A decrease in precipitation and/or increase in temperature increases their vulnerability to oxidation and loss of thicknessand area. It has been suggested that, under climate change, the volume of peats in agricultural use will shrink by as much as 40%. Some peat soils in the UK (e.g. the fens of East Anglia) are associated with acid sulphate conditions that become accentuated as soils dry out and the sulphides they contain convert to sulphates. The resulting acidity hinders agricultural use, especially because the incorporation of lime is more difficult at greater soil depths.

3.3 WATER CONSERVATION

Agriculture and horticulture currently account for 1-2% of the water abstracted from rivers and boreholes in England and Wales. The majority of this is for outdoor irrigation. Although irrigation is a relatively small use compared with public water supply and industry, it is significant in some catchments. Irrigation is concentrated in particular areas within the drier regions (almost half is used in East Anglia) and the water is mostly abstracted during a few summer months, peaking in the driest years when resources are scarcest. Irrigation water use has been growing at an underlying rate of 3% per annum from 1982 to 1995. Continued growth is predicted for the future, with a 50% increase by 2021 under the 'most likely' scenario but ignoring climate change. Already, additional licences are unobtainable in some catchments in some of the most important irrigated areas. Climate change may well reduce available resources in precisely those regions and at those times when agricultural irrigators most need it.

A number of factors interact to determine the impact of climate change on agricultural water use.

- Irrigation needs are determined by the drier years, rather than average years. An increased frequency of extreme years could have more effect than changes in the average values.
- Existing irrigated crops may require more water, others may require less.
- Farmers may wish to irrigate new or existing crops that are not irrigated at present.
- Automated irrigation equipment may encourage larger application depths.
- Water conservation measures could become more economically viable.

Changes in irrigation demand

Changes in the net volumetric irrigation demand depend on changes in land use, the proportions of the crops irrigated and the depths applied to those crops.

In the UK, irrigation is supplemental to summer rainfall, in contrast to the situation in arid climates where summer rainfall may be negligible. Seasonal irrigation need is determined by the running balance between crop evapotranspiration and effective rainfall in the May to August period, with the soil in the root zone providing a short-term buffer. If evapotranspiration increases or rainfall declines, irrigation need on existing irrigated crops will be increased.

In North Kent, a 2°C temperature rise from April to August would increase evapotranspiration by 5-15% and increase potential soil moisture deficits by 10-35%. The theoretical irrigation need in a dry year is related roughly linearly to potential soil moisture deficit. A 10% increase in the potential soil moisture deficit would lead to increases in irrigation needs of the design dry year of around 8-12%, depending on crop type and soil. Combining these results suggests that a 1°C increase in summer temperature alone would increase the irrigation need of the design dry year by 5-17%.

For a temperature increase of just over 1°C over the summer months and little change in summer rainfall, quantitative relationships between past climate variations and irrigation abstractions, an additional 27.5% demand above current trends is estimated in East Anglia by the year 2021.

These estimates are sensitive to changes in sunshine hours and relative humidity, factors that are also likely to change. Extra sunshine and lower humidity, if associated with increased temperature and lower summer rainfall, would lead to larger increases in irrigation need. Clearly, more detailed knowledge of other aspects of climate change, beyond temperature and seasonal rainfall, is needed to obtain better predictions.

Areas irrigated

The largest increase in water demand could potentially come from an increase in the area irrigated.

Figure 3.3 maps the extent and location of demand for irrigating existing crops. Most irrigation water in the UK is applied to a very limited range of crops. Over half is used just on potatoes, with sugar beet and certain vegetables also significant users. The vast majority of potatoes are likely to be irrigated by 2021, with or without climate change, but for most other crops only a small proportion of the total planted area is irrigated. The present benefits of irrigation (e.g. quality, yield and timely supply) vary tremendously. Irrigation of potatoes and some

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vegetables can be very profitable. Full irrigation of sugar beet is only economic without reservoir storage costs, and full irrigation of grass and cereals cannot justify new capital costs. These results agree with the observed changes in the areas of crops currently being irrigated.

However, the advantages of irrigating (or the penalties of not irrigating) would increase if climate change leads to more yield losses and quality losses due to water stress. The effect on irrigation would depend greatly on the possibility and cost of obtaining the additional water.

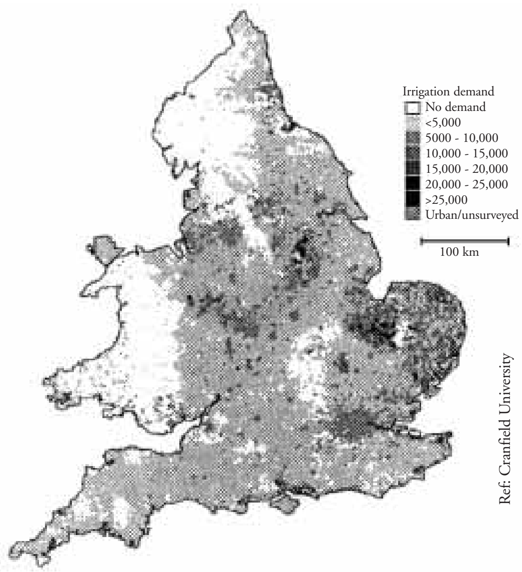

Figure. 3.3: Total volumetric irrigation demand (m3 km^{-2}) in a design dry year in 1995, for all crops irrigated. Source: Weatherhead *et al.* (1997).

Land use and agronomy

Even less predictable are the effects on irrigation of changes in land use due to climate change. Irrigated maize in northern and central France is a major water-consuming crop, but is almost unknown in the UK. If the UK climate warms and dries, grain maize may become more common and forage maize more widespread and irrigation would then become necessary. On the other hand, it may be possible for existing irrigated crops, including potatoes, to be grown further north or west, where irrigation need is lower. Earlier planting and harvest dates may also become possible, avoiding periods of peak moisture demand. A critical factor may be whether or not early season frosts become less common. Similarly, warmer drier weather would allow easier cultivation of heavy soils (see above), perhaps slowing or reversing the trend to grow root crops on lighter soils which then demand more irrigation.

On-farm water conservation

Most irrigation in the UK is currently applied through hose-reel irrigators fitted with large sprinklers or guns. These mobile systems are inaccurate, but are well suited to mechanised UK farms, rotational cropping patterns and relatively low irrigation needs. Better technical performance can be obtained, for example with booms, centre pivots, linear movers or possibly trickle (drip) systems. Modern scheduling systems can also help. It can be hard to justify the higher costs of these systems at current abstraction prices, but water scarcity is likely to encourage farmers to pay more attention to efficiency. Climate change is likely to increase the value of water and to spread unit costs over larger volumes, so reinforcing the present gradual change to more efficient application systems.

Paradoxically, this may not reduce water use. All these systems have higher fixed costs but lower variable costs. Farmers may therefore decide to irrigate more intensively, offsetting some or all of the efficiency gains.

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Construction of on-farm winter storage reservoirs is financially attractive for farmers irrigating high-value crops. The total volume stored is increasing rapidly, and this growth would be accelerated by increased demand from climate change. However, *winter* water availability would then become a constraint in many catchments. Decreased winter flows would have serious implications for reservoir owners.

On-farm water harvesting, from roofs and paved areas, is possible, especially in regions of water scarcity. The direction of change in summer rainfall will be crucial in deciding whether this becomes more common or uneconomic.

In practice, limits on water availability will determine irrigation use, rather than the unconstrained demand forecasts discussed above. Shortages will lead to a higher opportunity value for water and the dominant issue would be how to use the available water most effectively. This means addressing the issue of where irrigation is most beneficial, rather than the narrower question of raising application efficiency, and has implications for the water allocation and licensing system.

Perhaps the only clear conclusion is that climate change would make predictions of long-term irrigation demand even less reliable. Catchment planners must allow for the possibility of substantial increases in both summer and winter demand, and promote flexibility in allocation. Designers of irrigation systems must build in enough flexibility to cope with possible unforeseen changes.

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The UK's current climate is particularly suited to temperate-zone arable crops with relatively good adaptation to cooler temperatures; yields of wheat, barley, oats and oilseed rape are among the highest in the world. The climate allows a wide variety of arable and horticultural crops to be grown with differing reliability and productivity.

Climate change will alter the potential in the UK for different crops, and the economic viability and competitiveness of different farm enterprises. This chapter reviews available research on major agricultural and horticultural crops and gives some specific illustrations.

4.1 ARABLE CROPS

Experimental studies have not been done on all crops, or even all the major crops grown in the UK. Also, studies relevant to the UK have largely been made under laboratory conditions. However, the responses measured are relatively consistent.

Many crops grown in the UK, with both determinate and indeterminate development, may benefit from enhanced CO_2 and warmer temperatures. However, using experimental results to draw conclusions about agricultural production should be done cautiously as changes in other factors (nutrition, water, pests and diseases and variety) are important determinants of yield.

Cereals

Two sets of experiments provide insight into the effect of climate change on winter wheat. Plastic tunnels at Reading were used to measure responses of several cultivars to elevated CO_2 and temperature. Experiments at Rothamsted simulated these conditions in the field (Table 4.1).

The Reading experiment showed that the beneficial effect of doubling CO_2 on grain yield in cultivars Galahad, Mercia and Soissons was negated by an increase in mean seasonal temperature of 0.7-2.0°C. The effects on grain and biomass varied considerably between cultivars.

At Rothamsted, the combined effect of CO_2 and +4°C was a decrease in yield of about 10%, approximately the average of the individual effects of CO_2 and temperature (Table 4.1). The temperature change in this experiment was too high to be offset by the beneficial effects of elevated CO_2.

The Rothamsted experiments also highlight the effects of climate change on different stages of growth. Winter wheat grew very slowly during the cold, winter period. CO_2, on its own, had no effect. However, the additional 4°C greatly increased tiller numbers and growth of tillers and leaves, and accelerated reproductive development.

Early season - up to anthesis

- CO_2 stimulated growth.
- Elevated temperatures increased biomass production.
- The main effect of both treatments was to increase the number of shoots.

Tiller death

- Many more tillers died in warm than cool conditions, so fewer ears were produced under warm conditions.
- This occurred in both CO_2 treatments, although elevated CO_2 reduced tiller death in both treatments.

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Grain filling

- Elevated temperatures increased the rate of grain growth but shortened the duration of grain filling.

- Higher temperatures may have decreased the availability of assimilates so decreasing grain size, grain yield and mass per grain.

- Higher temperatures reduced average mass per grain, in one experiment, by 25% in normal CO_2 and 14% in elevated conditions. An exception occurred where partial sterility caused by high temperatures decreased grain number and the surviving grains were very large.

Elevated CO_2 decreased the nitrogen concentration in all plant tissues (in grain by about 10%) but did not affect protein proportions. Warmer temperatures had marked effects on the quality of grain lipids in winter wheat, decreasing the amounts of non-starch and starch lipids, particularly non-polar lipids. There were changes in the proportions of major lipids. Such changes will affect the bread-making quality of wheat: similar changes in other grains or produce could also affect industrial and nutritional uses.

Straw production will also increase with elevated CO_2 and warmth, similar to grain yield. The harvest index (the ratio of yield to above-ground biomass) will decrease. The relative impact of both CO_2 and temperature is greater on root dry mass than on either grain yield or total dry mass. Increased straw production will require management; if incorporated into the soil, organic matter will increase. Increased roots will also increase soil organic matter. Increasing drought will affect all cereals, especially on light land, but the rising levels of ambient CO_2 may reduce transpiration, helping to conserve water.

Similar effects of CO_2 and temperature have been observed on other varieties of winter wheat. Also, studies on spring wheat show the same trends although the size of the response and impacts on tiller number are somewhat smaller than in winter wheat. The beneficial effects of elevated CO_2 were much reduced when nitrogen supply was deficient.

Sugar beet and potato

Sugar beet is normally grown as an indeterminate crop. As with winter wheat, beet was grown in simulated field conditions at Rothamsted with combinations of current and elevated CO_2 and temperature (Table 4.1). Growth and number of leaves increased substantially with increased temperature, particularly in the early season, thus increasing radiation interception, but CO_2 had little additional effect. Limiting nitrogen supply decreased growth (leaf number, individual leaf size and leaf area) and so limited radiation interception, but did not alter the basic response to temperature. However, warmer temperature decreased leaf area and radiation interception late in the growing season due to earlier maturity, senescence and dormancy.

The effect on production of a 3°C increase in temperature was to decrease total dry matter by an average of 10% and root total dry matter by 7%. The explanation for this decrease in dry matter is increased respiration and a shorter growing period. In contrast, elevated CO_2 increased total dry mass by 21% and 11% and root dry mass by 26% and 12% for high and low nitrogen treatments, respectively.

Quality of sugar beet is of concern in the extraction and purification of sugar. High sucrose concentrations are beneficial and increase yields per unit of beet extracted. Warm temperatures only slightly decreased the sucrose concentration.

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Sucrose concentration was not affected by elevated CO_2, but increased with low nitrogen.

The combined effect is beneficial for sugar beet yields at these temperatures and with elevated CO_2.

Fodder beets, swedes, potatoes and other root crops may be expected to show similar responses. With elevated CO_2, potatoes will probably show an increase in the number of tubers rather than an increase in tuber dimensions. Warmth will accelerate development, and crop modelling indicates that tuber yields will increase by about 10%. Quality may change as protein to carbohydrate ratios decrease with elevated CO_2.

	Year	Control yield (t/ha)	Change in yield (%) with elevated CO_2	Temp.	CO_2xTemp.
Winter wheat	1990/9	1173	+16	-19	-7
	1991/9	800	+37	-35	-9
	1993/9	612	+12	-25	-11
	Mean	861	+22	-26	-9
Sugar beet	1993	1748	+20	-9	+10
	1994	1466	+37	-12	+22
	1995	1852	+26	-4	+26
	Mean	1689	+27	-8	+19

Table 4.1: Effects of elevated CO_2 and temperature on yields of winter wheat and sugar beet.

Notes: Experiments at Rothamsted for winter wheat (cv. Mercia) and sugar beet (cv. Colt) with temperature and CO_2 simulating field conditions, with adequate water and nitrogren.

The effect of CO_2 is for an increase from 360 to 700 ppmv. The effect of temperature is for +4°C for wheat and +30°C for sugar beet. The combined effect (CO_2 x Temperature) is the ratio (as a percentage) of the effect of both treatments compared to the control. Growth was under natural daylength, with natural radiation supplemented with artificial light to give intensities 70-80% of ambient radiation.

Other crops

Soya bean has been well studied and responds very positively to elevated CO_2. Protein crops may be more sensitive to interactions between conditions because of the need for a nitrogen supply, correct temperature and water conditions and the large energy needs for protein synthesis.

Experiments with clover show that root growth and nodulation are greatly increased by elevated CO_2. Nitrogen fixation is expected to be stimulated by the availability of energy and assimilates as substrates for reduced nitrogen. Substantial increases in clover yields may be expected; up to 45% in 680 ppmv CO_2. The extent may depend on the degree of nodulation and nodule activity. No detrimental effects of warmer temperature were seen on clover.

Assessing the responses of field beans is difficult because so little is known about the causes of yield variability under current conditions. They may respond similarly to clover with a substantial increase in yield due to CO_2 and, if the crop requires warmth, climate change may be advantageous.

Crops such as oilseed rape, sunflower and linseed may react to climate change rather like legumes, because they require a good deal of energy to synthesise their oils. It is possible that oilseed rape will respond to CO_2 rather more than other C3 plants but 20-30% increase in production has been calculated using a climate change scenario for 2080.

The lack of field experiments on many temperate crops hampers clear understanding of specific impacts of climate change on development, yield and yield quality. However, it is important to bear in mind that over the last few decades average yields of cereals have increased by 1-2 % per year as a result of improved management. If this rate of improvement continues in the future, the effects of these gradual technological improvements are likely to outweigh the effects of climate change.

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4.2 HORTICULTURE

The effects of climate change on field vegetables, top fruit, soft fruit and protected crops are considered in this section.

Field vegetables

The successful production of field vegetables has relatively little to do with high yields of dry matter. Far more important for vegetable growers is the timing of maturity, crop uniformity, and product quality. Changes in temperature will affect all these aspects.

Responses of different vegetables to higher temperatures are reviewed in this section. The responses are generalisations and, where higher temperatures create problems, some of these can be avoided by selecting a different variety. Those species that are most likely to benefit commercially from increased temperature are phaseolus bean, onion and sweetcorn.

Brassica

Cauliflower is an example of how temperature effects can be complex. Cauliflowers have three distinct phases of growth during which the response to temperature differs: juvenility (early leaf growth), vernalization (when specific temperatures are necessary for curd initiation), and curd growth.

Higher temperatures will shorten the periods of juvenility and curd growth but delay curd initiation (see Figure 4.1). Higher temperatures are likely to advance the maturity of early summer crops but may delay the maturity of autumn crops, so that transplanting schedules will need adjustment to maintain continuity.

Higher temperatures may also increase quality problems with bracts, leafy bracts and curd looseness but will reduce frost damage and riciness. The potential area of Roscoff and winter-hardy cauliflowers could increase with a milder climate. However, even at present the impact of small changes in mean temperature, which are close to the critical temperature for vernalization, are disrupting production by making it difficult to schedule continuous crop production. Where crops mature more rapidly it will be necessary to plant smaller areas of crop more frequently in an attempt to smooth out supply fluctuations.

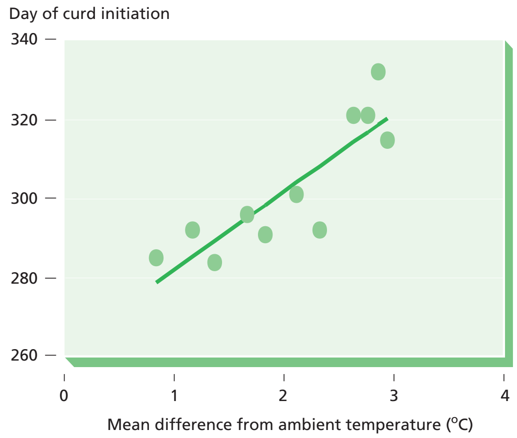

Figure 4.1: Day of curd initiation (1 January = 1) for Roscoff cauliflower plotted against the temperature difference from ambient averaged over the time period from transplanting to curd initiation. Source: After Wurr, Fellows and Phelps (1996).

Root crops

Higher temperatures will aid carrot production. Carrot growth rates increase with temperature, and growth occurs best at soil temperatures of 20-30°C. Earlier production under polythene will be possible, extending the growing season as frost damage on field crops will be reduced.

Experiments at Reading have shown that elevated CO_2 has a larger effect on root yield than on total biomass. A 31% increase in yield resulted from an increase from 348 to 550 ppmv in CO_2

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concentrations, compared with a 16% increase in total biomass. This enhanced response is expected in a crop such as carrot, where the root yield component is a relatively large sink.

Allium

Onion seedlings grow fastest at 23-27°C and plants require maximum vegetative growth before bulbing, which is promoted at higher temperatures. The optimum root temperature for rate of increase in bulb size and for maximum bulb diameter is about 24°C. Thus higher temperatures will give earlier bulbing, faster bulb growth and maturity and should improve skin quality (see Figure 4.2) but may reduce yields because the duration of bulb growth is reduced.

Elevated CO_2 also affects both development and growth in onion. Increases in dry matter in high CO_2 will more than offset the effect of season shortening due to increases in temperatures. Long-season varieties will benefit more than short-season ones.

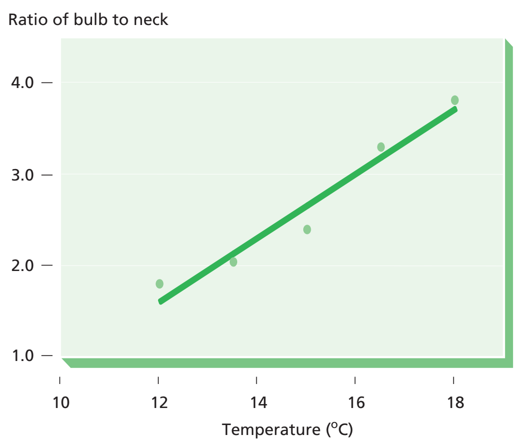

Figure 4.2: Bulb development of onion expressed as the ratio of maximum bulb diameter to minimum neck diameter against average temperature. A high ratio indicates good quality bulbs. Source: D. Wurr, HRI.

Salad crops

Lettuce will germinate better if temperatures are warmer early in the growing season, but high temperature dormancy will be more of a problem in mid-summer. Suitable temperature ranges for growth are a minimum of 3-12°C and a maximum of 17-28°C, with an optimum mean temperature at maturity of about 15°C. Higher temperatures will shorten the growth of individual crops and extend the season of production. However, the production of heads of adequate quality will be more difficult during peak summer months because loose heads, tipburn, bitterness, russet spotting and bolting are more likely.

Legumes

Phaseolus beans, which are sensitive to air temperatures less than 10°C, are likely to have improved germination and growth, a faster rate of leaf production, earlier flowering, an extended growing season and increased yield. Production of navy beans throughout parts of southern England will be more viable because the heat unit requirement for full crop growth will be achieved earlier and more reliably.

Cucurbits

Marrows and courgettes cannot tolerate long periods below 10°C and grow best at mean temperatures of 18-30°C. Higher temperatures will therefore help growth, extend the growing season and increase yields.

Horticultural cereal

Sweetcorn will not germinate below 10°C and needs soil temperatures greater than 13°C before drilling. The optimum air temperature for growth is 21-30°C but the crop can be grown at temperatures from 16-35°C. Thus higher temperatures will enable more rapid growth and the potential area of sweetcorn grown in the UK will expand to the north. Yield (dry matter for silage, fodder and grain) might increase by 10-15% for a 2°C warming. Cold periods in spring, even if summers were warmer, would limit the crop but a longer growing season would help ripening.

Social and economic factors

The impact of climate change on the area cultivated in each crop also depends on social and economic factors. For example, although growing conditions will improve for vegetables such as turnip and swede, production may contract as consumers choose more exotic vegetables, which can be grown in the UK as conditions improve.

Top fruit

Climate change may be more relevant for perennial top fruit than for crops that are grown annually. Decisions made now will affect production for the next several decades, coinciding with the period when climate change could have significant effects.

It is not feasible to develop orchards of new cultivars rapidly enough to give varieties that are better able to tolerate the stresses of changing climate. The fruit varieties and rootstocks used in new orchards were bred many years ago with little interest in climatic tolerance; the economic outlay required for planting discourages subsequent change.

Temperature responses

Perennial fruit crops have a complicated relationship with climate - in particular with temperature. Temperature minima and maxima can be important, but so also can the predictability or consistency of temperature during critical phases of development.
For example, during late autumn changes in both daylength and the reduction in daily temperature induce dormancy and leaf fall.
The time at which fruit trees become dormant has important implications for the 'quality' of the flower buds (potential to set and retain fruit) and the time at which flowering occurs. Before bud break can occur, buds have to receive a predictable amount of exposure to low temperatures between 0 and 10°C (about 100 hours for apple). It has been estimated for Cox's Orange Pippin, grown in Kent, that an increase of 2°C would advance bloom date by about 18-24 days. After the dormant period, the rate at which buds develop (the forcing period) is also determined by temperature.

It is particularly important that, once forcing has started, the floral buds do not fall below critical temperatures, or low temperature injury will occur. Therefore, any advance in flowering induced by climatic change would bring with it an increase in the susceptibility of flowers to frost damage.

With some apple varieties (Cox's Orange Pippin) above-average temperatures both before and around blossom time can have negative effects on fruit set and cropping. These effects are independent of those associated with the injury caused by subsequent exposure to low temperatures.

Water responses

Fruit size is important in maximising economic return in top fruit growing. Early apple fruit growth, in the first six weeks after full bloom, occurs primarily by cell division that is sensitive to temperature. It is important to maximise the number of cells within an apple, as this has considerable influence not only on final fruit size, but also on fruit texture and storability.
Availability of water becomes important after the cell division phase, when fruit growth occurs by cell expansion. If the availability of moisture decreases due to increased evapotranspiration

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and/or decreased precipitation (as predicted in some climate change scenarios) then the future economic viability of top fruit in southern England may rely on increased irrigation across large areas. Orchards may be particularly suitable for trickle irrigation, as pipes can be installed on a permanent basis.

Radiation responses

Fruit cropping and fruit growth are also clearly influenced by solar radiation, and economic fruit production is achieved by maximising tree light interception. However, radiation levels in the UK are frequently a limiting factor in the production of quality fruit. Any increase in cloud cover will reduce solar radiation and have deleterious effects on the yield of fruit. Some crops, such as cherries, are particularly sensitive and the production of quality fruit can be severely limited even by short periods (1-2 weeks) of low radiation at critical times in their growth and development.

Soft fruit

The soft fruit industry in the UK is made up of a number of different crops, including strawberries, raspberries, blackcurrants, red/white currants, gooseberries, blackberries and hybrid berries. Of these, strawberries are predominant followed by raspberries and blackcurrants, with these three accounting for around 95% of the total area.

Soft fruit show a wide adaptability to current climatic variations across the country, being grown in most regions of the UK. Given the most likely predicted changes in UK climate, it seems probable that there will be few dramatic effects on most soft fruit production. Moreover, compared with top fruit, relatively rapid development and introduction of new cultivars that are better adapted to altered climatic conditions, will be possible. However, an increase in the mean air temperature and a possible reduction in summer rainfall will have effects on the cropping season, patterns of production and the spectrum of pests and diseases. Perhaps most importantly for soft fruit, water usage for irrigation may become more critical.

The use of trickle irrigation, which allows for more efficient use of water, is widespread in the soft fruit industry, particularly for strawberries. If an increase in temperature is combined with a reduction in summer rainfall, there will be increased pressure for water to be used more efficiently.

A general warming of the climate will extend the potential growing season of soft fruit, both in the open and under protection, and this could lead to a greater availability of UK-grown produce throughout the year. However, higher temperatures will tend to increase the rate of ripening of an individual crop, so that a wider range of varieties will have to be grown to exploit the full growing season.

Protected crops

Protected crops in the UK include tomato, cucumber, sweet pepper, chrysanthemum and various kinds of pot plants. Since the purpose of protected cropping is to provide a relatively controlled environment that insulates plants from the vagaries of weather, the impact of climate change is unlikely to be as great as with field crops. If present crops and systems of production continue to be used, less fuel will need to be burnt to maintain set temperatures for heated crops.

As plant growth in commercial glasshouses is normally boosted by adding CO_2 to the glasshouse atmosphere, slightly less CO_2 will be required to maintain the desired concentration of 1000 ppmv CO_2 in winter. Together with the requirement for less heating, this means that the

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impact of climate change is likely to be beneficial in winter. Higher ambient CO_2 concentrations should also be beneficial in summer because growth of most glasshouse crops increases almost linearly with increasing CO_2 concentration in the range 360-500 ppmv CO_2.

It is in the summer, however, the adverse effects of global warming are likely to be encountered. For example, an increase in air temperature will lead to higher temperatures under glass and to impaired quality. If the salinity of irrigation water were to increase due to intrusion of sea water, this would also reduce crop yields and increase the incidence of physiological disorders that are affected by salt concentration, such as blossom-end rot of tomato. One major area of uncertainty is the impact of climate change on cloudiness. An increase in cloudiness will reduce the amount of solar radiation and thus reduce crop yields.

The adverse effects of global warming on the production of protected crops might be lessened in various ways. First, there is potential with many crops to select for varieties with greater tolerance of high temperatures. Secondly, the cultivation of certain crops may be relocated to areas more favourable for their production in the future, as has happened in the past. However, a general increase in air temperature would add to the market pressures on heated crops. Extension of the production season for crops grown in unheated glasshouses, plastic structures or in the open would compete with the market for produce grown in heated greenhouses.

Box 4.1
Impact of a rise in sea level on agriculture

The global rise in sea level by 2050 is expected to be 10-50 cm. In the UK, the relative rise in sea level depends on vertical land movement. Sinking of land in the east and south could double the global rise in sea level, while land rising in the north would reduce the risk substantially.

The principal effects of a rise in sea level are on inundation, erosion and salinity of fresh water. High tides and storm surges would be enhanced, particularly if coastal storms could also increase patterns, due to stronger winds or different orientations. Coastal flooding would accelerate erosion. Higher sea levels will lead to greater intrusion of salty water into estuaries and groundwater.

At greatest risk are areas of rapid erosion, low-lying coastal areas and estuaries, with 400,000 ha in the fenlands alone. The Wash and the Norfolk and Suffolk coasts, Morecambe Bay and Somerset Levels are relatively vulnerable. Altogether, some 57% of grade 1 agricultural land in the UK lies below the 5 m contour.

The effects on agriculture will be varied. Damage to crops and livestock (e.g. grazing on drained marshes) at the time of flooding is a short-term threat with considerable costs. Erosion of coasts is of limited general impact on agriculture, although some coastal farms would be affected.

The long-term prospects of salinisation and waterlogging of soils with rising water tables are more significant. Saline water, for example from estuaries, may penetrate into upper soils, affecting plant growth. Incursion of saline water into aquifers and estuaries may affect water supplies in some areas, particularly if rainfall decreases.

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The impact of salinisation is likely to be more severe on horticultural crops, which are commonly irrigated, than for arable crops. With horticultural crops concentrated in areas such as the fens, the impact of a relatively small degree of salinity could be disproportionately large. Plant responses to salinity and waterlogging are reasonably well understood, although the basic mechanisms are complex and the reasons for differences between species and between varieties are not quantitatively assessed. Adaptation to salinity involves the ability to exclude or sequester sodium and chloride ions. Coping with waterlogging requires adaptation to poor aeration (elevated CO_2, decreased oxygen) and accumulation of reducing substances including reduced forms of iron, manganese and nitrite.

Interactions of these stresses with the other effects of climate change have been little studied. Elevated CO_2 may decrease the uptake of ions such as sodium because of the decreased transpiration resulting from smaller stomatal conductance. Also, the increased availability of carbohydrates may help to provide energy for mechanisms of salt exclusion, secretion or sequestration. The effects of the interaction of temperature rise with salinity is unknown. With waterlogging, however, elevated CO_2 may make conditions worse due to greater CO_2 in the soil. Warmer temperatures will make conditions in waterlogged soils worse because of the higher rates of oxygen consumption by soil organisms and roots.

Wheat is less tolerant of salinity than barley. Sugar beet is a naturally salt-tolerant crop and may benefit from some additional sodium. A range of salt-tolerant grasses is available and already provides much grazing on drained salt marshes.

Oat is traditionally a crop of wet, poor nutrient conditions and is likely to be more adapted to waterlogging than wheat and barley. Legumes, especially if well nodulated, are intolerant of waterlogged conditions. Horticultural crops may be more sensitive than arable crops because their yield quality is particularly sensitive to stressed conditions. Winter waterlogging may damage crops but drier soils in spring allow regrowth, which often compensates well. Spring or summer waterlogging would cause more damage because of limited capacity for regrowth.

Worldwide, there is a range of genetic material showing tolerance to salinity and waterlogging, which could be used for breeding crops for UK conditions. However, the demand for such crops may be small and not justify the investment. Opportunities for maintaining crop production under increasingly saline, waterlogged conditions are currently restricted to amelioration of the impacts, by drainage and irrigation with good quality water to wash out salts, and by changing to less sensitive crops.

A rise in sea level is thus most likely to have local effects on horticultural rather than arable crops. In most of the vulnerable areas, present sea defences and artificial drainage manage water levels. For the next few decades, maintenance and pumping costs may increase but large-scale change would not occur until later in the next century. Some small areas may become uneconomic to maintain. As problems occur, gradual replacement of sensitive crops and enterprises will reduce the impacts.

4.3 UNCERTAINTIES

Understanding the impact of climate change on crops must encompass the range of climatic changes, their effects on soils and hydrology, the potential interactions with a rise in sea level, and the individual responses of crop varieties. This is a huge undertaking and many uncertainties remain.

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The key uncertainties are probably in the interactions between crops and their environment, regarding the following factors.

- *Extreme events.* All crops are sensitive to extreme climatic events, but not necessarily the same ones. The balance of effects on cropping systems depends on which local climatic hazards become more important: frost, heat waves, drought, floods, waterlogging, windstorms and hail affect production, yield and yield quality to varying degrees. A small shift in mean conditions, with a greater shift in the risk of climatic extremes could have significant effects, particularly on quality.

- *Regional water supplies.* The balance of supply and demand is difficult to estimate at present. Key factors include: (a) effects of CO_2 enrichment on water-use efficiency, (b) effects of temperature, wind and humidity on evapotranspiration, length of the growing season and crop-water demand, and (c) changes in the use of irrigation.

- *Biomass and soils.* The interactions of changed crops, crop yields and cropping seasons with soil processes will affect soil texture and quality through the amount of organic matter returned to the soil and its decomposition.

Despite these uncertainties, there is some confidence that rising CO_2 concentrations will be beneficial and warmer temperatures will expand the range of crops that can be grown in the UK. Conditions are unlikely to be so extreme in the next few decades that our current crops will not be viable.

Box 4.4

Impacts of a change in European climate

Climate change and its impacts will not be limited to the UK. Recent research suggests that regional changes in Europe will often parallel expected impacts in the UK.

• As in the UK, the occurrence of agriculturally significant extreme events is altered by relatively small changes in climate. The probability of exceeding crop-specific high temperature thresholds increases with climate change, resulting in a significantly higher risk of crop failure in parts of southern Europe. The length of the frost-free period will increase, enabling new crops with higher thermal requirements and lower frost tolerance to be cultivated in northern Europe.

• The yields of C3 crops (vegetables, grapes, wheat) will generally increase with climate change due to large beneficial effects of CO_2 on photosynthesis. This compensates for the negative effects of warmer temperatures on yields, which cause a reduction in the duration of crop development stages. In contrast, the yields of C4 crops (maize) decrease due to limited benefit gained from CO_2 enrichment. Interactions with altered precipitation and increased evapotranspiration may affect the response.

• Current differences in crop productivity between northern and southern Europe increase under climate change. The countries of northern Europe benefit by being able to grow a wider array of crops than are currently possible due to a warmer and longer growing season. Crops which are currently grown throughout Europe experience more positive impacts in northern Europe compared with southern Europe.

• The inter-annual variability of crop yields changes with mean climate change. In regions where crop production is affected by water shortages, such as in southern Europe, increases in the year-to-year variability of yields in addition to lower mean yields are predicted.

Source: *Climate Change and Agriculture in Europe*, results of the CLAIRE project funded by the European Union.

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5. Arable Weeds, Pests and Diseases

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Interactions between arable crops and weeds, pests and diseases may alter with climate change, affecting the productivity and competitiveness of different farm enterprises.

5.1 WEEDS

To cope with climate change, farmers may change the varieties or even the crops that they cultivate. It is unlikely that crops will evolve on their own to adapt to the new climates. In contrast, weeds that compete with crops can evolve very quickly. Before farming was invented, most weeds did not exist In their present form. Hence, many weeds have become established, in less than 8000 years, as a result of evolutionary adaptations to agricultural conditions. In more recent years, many weeds have become tolerant to a range of herbicides, demonstrating how rapidly they can evolve to evade new control measures.

Herbicide tolerance is a good example of a 'co-evolutionary' race. Predators and diseases continue to challenge human health, livestock and crops. No sooner has a challenge been solved, than the challenger finds a new way of avoiding the protective strategy. For example, blackgrass has developed resistance to herbicides, and mosquitoes have developed resistance to DDT and other insecticides.

Changes to climate are likely to influence the ability of weeds to compete, in ways that are not easy to predict and have deeper implications than a mere adaptation to the change itself. The advent of longer, warmer growing seasons might allow new species of weeds to compete with crops. However, most research has focused on understanding how current weeds are likely to evolve as climate changes. This will help to formulate effective response strategies.

Evolution has two components. Firstly, a new gene or genes must originate in a population either by mutation or by transfer from another population. This process is essentially independent of climate. Secondly, the rate at which the new gene becomes established in a population *(evolutionary rate)* will depend on the generation time of the weed, its population size, and the success *(fitness)* of the new strain. All of these factors might be influenced by climate, which might therefore affect evolutionary rate.

Generation time

The more generations per unit time, the faster will be the potential rate of evolution. The longer and warmer the growing season, the more generations a weed can achieve in that season and, potentially, the faster its rate of evolution.

Population size

Populations might encounter more stresses from heat and drought as climate changes, causing periodic catastrophic reductions in population size. Such evolutionary 'bottlenecks' increase chance effects and tend to influence both the rate and the direction of evolutionary change.

Fitness

Some newly establishing genes may not have the same climatic tolerance as those already present. For instance, many herbicide-tolerant species require different temperature and light conditions for rapid growth than herbicide-sensitive plants.

To study the effects of climate change on generation time, population size and fitness, and, hence, on the evolutionary rate of weeds, a number of experimental studies have been conducted for key weed species in the UK.

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Experiments on the evolutionary rate of weeds

Experiments were undertaken at Newcastle-upon-Tyne on familiar agricultural weeds whose genes are likely to vary in terms of fitness for different climatic conditions. These included paraquat-tolerant strains of ryegrass, triazine-tolerant strains of fat hen and nave weed, and field spurrey. The experiments investigated the likely effects of average temperature changes of +1°C and -1°C compared with the present climate. Which variant won the evolutionary race in a given environment and how quickly it did so were measured. The data were then examined to evaluate whether generation time or population size affected evolutionary rate.

A pasture or lawn grass, such as ryegrass *(Lolium perenne)*, usually reproduces vegetatively by producing new shoots. Each new shoot can be thought of as a new generation. In the experiments, growth and generation time were much faster in the warmer plots. The paraquat-tolerant strain of ryegrass adjusted in four months under these conditions (Figure 5.1). In the cooler plot, however, evolutionary rate was much slower and equilibrium was only reached after two years. Hence, in this species at least, a warmer climate is likely to favour paraquat-tolerant strains.

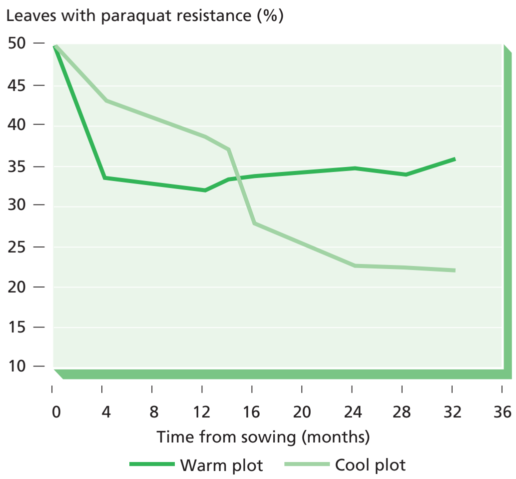

Figure 5.1: Evolutionary rate of paraquat-tolerant leaf blades of rye grass.

The frequency of triazine-tolerant plants of nave weed was low for all conditions, although tolerant plants stabilised at a frequency of about 20% in warmer conditions. In cool and dry conditions, tolerant plants disappeared from populations entirely (Figure 5.2).

However, in fat hen, the frequency of triazine-tolerant plants stabilised at a much higher level, forming 60-80% of the population. In warm wet conditions, tolerant types may occur exclusively.

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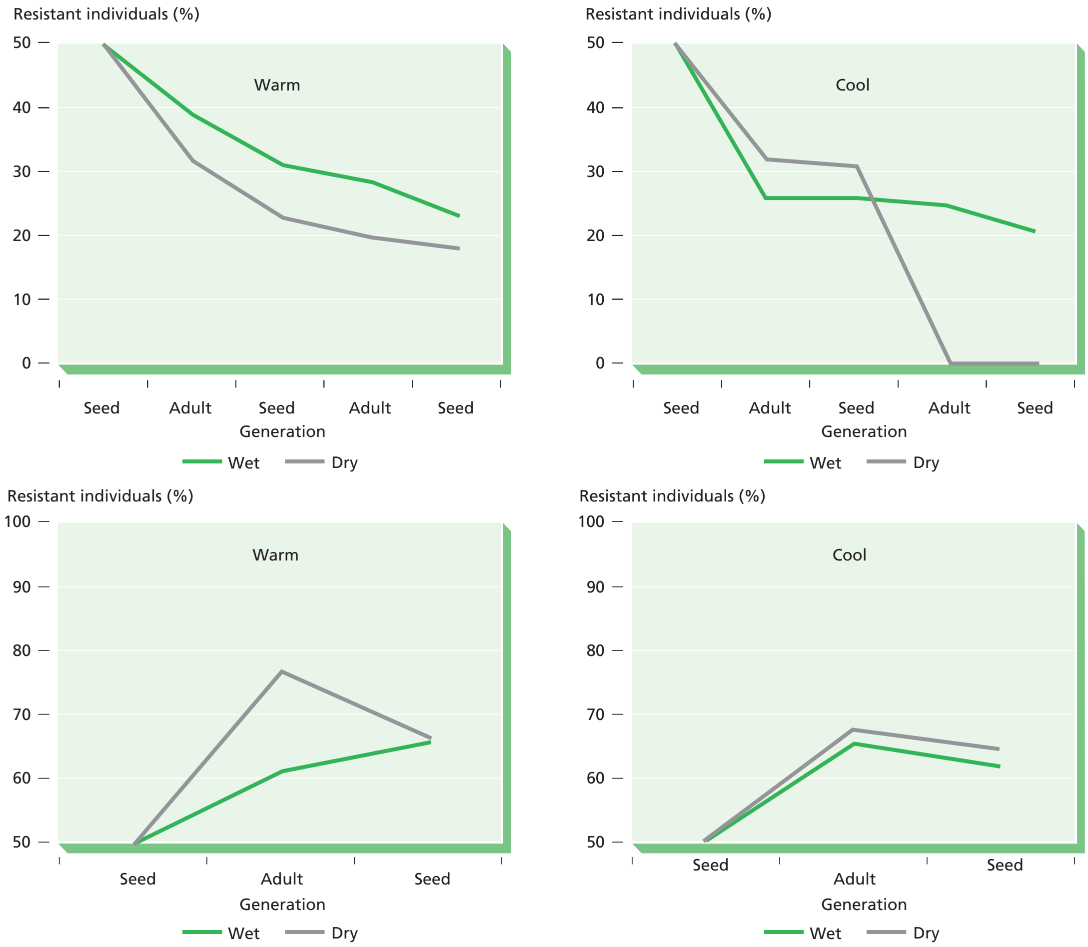

Figure 5.2: Frequency of triazine tolerance in nave weed (top) and fat hen (bottom).

Nave weed and fat hen are large, relatively slow-growing weeds that normally complete only one generation in a year. Not surprisingly, evolutionary rates did not differ between the warm and cool plots.

Field spurrey *(Spergula arvensis)* matures more quickly than nave weed and fat hen, commonly completing two or more generations per year. Field spurrey populations in southwestern UK have seed coats with external 'pimples' *(papillae)*. These enable them to absorb soil water more readily than the populations with smooth-coated seeds that predominate in the northeast. In the vicinity of Newcastle-upon-Tyne, about 25% of the plants in wild populations have papillate seed coats. After five generations, experimental populations which started at 95% and 5% papillate all became 6-42% papillate (Figure 5.3), close to the local average.

This is a clear example of a weed evolving very rapidly (in five generations) to suit its environmental conditions. Although overall evolutionary rates did not differ between treatments, there was a striking difference in the

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progress of evolution between plots which received normal rainfall ('wet') and those which were protected from rainfall ('dry') (Figure 5.3). Evolution was gradual in the wet plots, taking place in a linear fashion. However, in dry plots evolution took place in a much less regular manner because populations were often decimated during dry spells. This is an illustration of the chance effects of evolution, occurring as a result of population bottlenecks in a stressful climate.

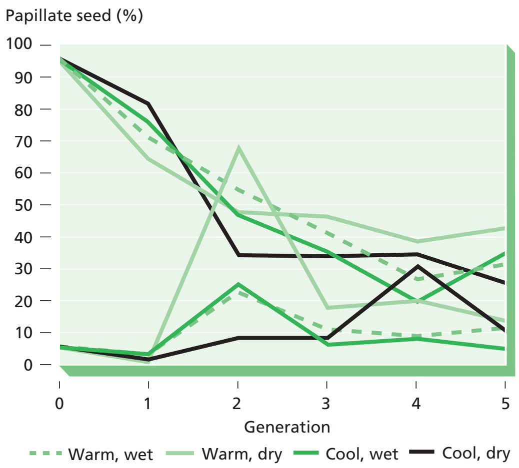

Figure 5.3: Change in the frequency of field spurrey with papillate seed coats.

5.2 PESTS AND DISEASES

The influence of climate on the distribution and dynamics of crop pests and diseases has long been appreciated and an understanding of the principles has underpinned attempts at forecasting the value of control measures. However, such forecasts have been short range - suggesting action in the succeeding few days or months at most. Contemplating the effects of climate change on pests or diseases years ahead adds a new and complex dimension.

Many interactions need to be considered when determining the impacts of climate change on pests and diseases. The rates of change in population growth of pests and pathogens are affected through survival, development, reproduction and dispersal, which are dependent to varying degrees on climate, particularly temperature, humidity, precipitation and wind. For example, milder winters are likely to increase the survival of some pests and diseases and allow their establishment in new locations. In warmer conditions, more generations of pests may be possible in a year. Some pest species go through as many generations in a year as temperature will allow, whereas others are limited by responses to daylength. More humid conditions tend to favour fungal pathogens; windy conditions aid dispersal of some pathogens and pests.

Climate change, as well as changes in levels of CO_2, pollutants and UV-B radiation, will affect not only the pests and diseases directly but also their competitors, natural enemies and host plants. These interactions may enhance or reduce problems. For example, higher CO_2 concentrations encourage more vigorous plant growth and a denser canopy within which the microclimate may be more conducive to disease development. The impact of pests and diseases is often related to the growth stage of their host plants. Climate change may disrupt the synchrony between host plants and their pests and diseases. The difficulty of properly taking into account all these interactions provides a major caveat to any prediction of pest and disease incidence in a future climate. Nevertheless, field and laboratory experiments, and empirical and mechanistic modelling studies, provide valuable insights into the sensitivity of some native and alien pests and diseases to changes in climate.

Arable Weeds, Pests and Diseases

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Native pests

The most comprehensive data set for any terrestrial invertebrate group is for aphids sampled using suction traps. Traps throughout the UK and Europe have been operated for up to 30 years. Some aphids reproduce all year round, whereas others produce winter eggs which are more tolerant of low temperatures than are active individuals. For species which overwinter largely in the active stages, strong correlations have been found between winter temperature and the timing and size of spring/early summer migrations. In the case of the peach-potato aphid (*Myzus persicae*), the start of the spring migration is expected to be about 29 days earlier, on average, by the year 2050 compared with the 1965-96 period (Figure 5.4).

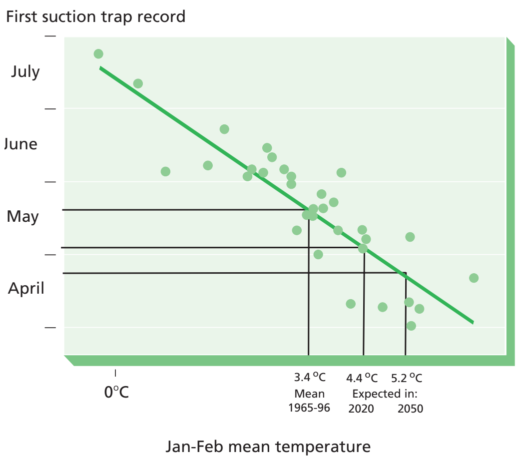

Figure 5.4: Relationship between the time of first occurrence of the peach-potato aphid in the suction trap at Rothamsted and mean temperature in January and February.

Surveys have shown that the northernmost UK distribution of the nematode (*Longidorus caespiticola*), which feeds on graminaceous plant roots, matches the 14°C July soil isotherm, restricting it to England, Wales and southeast Scotland. A 1°C rise in temperature would allow its range to extend and threaten all fertile land in Scotland. A northward shift is also expected in the distribution of the brassica pod midge (*Dasineura brassicae*), a major pest of oilseed rape. The insect is also expected to pass through more generations in a season.

Computer simulations of the development of the cabbage root fly (*Delia radicum*) suggest that a 3°C rise in mean daily temperature would lead to the species becoming active a month earlier than at present. The current maximum of three generations per year would not, however, increase to four unless the mean temperature increased by at least 5°C. Simulation models have also been used to assess changes in the development of the codling moth (*Cydia pomonella*) and the summer fruit tortrix moth (*Adoxophyes orana*) with climate change. Development of both pests is advanced by about 10 days with a 1°C rise in temperature. An increase of 2°C allows an extra generation of the summer fruit tortrix moth.

Studies do not always suggest that UK pest problems will increase. Some species, for example the New Zealand flatworm (*Artioposthia triangulata*), are adapted to thrive in cool conditions and these are likely to decline as the climate warms. The geographical range of wheat bulb fly (*Delia coarctata*) is also expected to decrease, based on expected changes in temperature and rainfall, except perhaps in northeast England and eastern Scotland.

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Native diseases

The response to climate change of diseases that depend on invertebrate vectors for their transmission will depend, in part, on the responses of the vectors themselves. For example, warmer winters will enhance the survival of cereal aphids and alleviate restrictions on their movement within crops. This is likely to increase problems from barley yellow dwarf viruses (BYDV), which they transmit, as has occurred in some of the exceptionally mild winters experienced in the last ten years. However, drier summers may help to reduce BYDV problems by limiting the supply of the aphids' alternative host plants, which bridge the gap between maturation of one crop and emergence of the next. The incidence of sugar beet yellow viruses also tends to be high after mild winters because of enhanced aphid survival and earlier activity in spring.

Many bacterial and fungal diseases depend on high humidity and rainfall for their transmission. How these climatic factors will change in the future is uncertain. However, temperature is also important in disease development.

Long-term data sets from surveys of wheat and barley diseases have been used to relate incidence to weather. For example, high levels of ear blight (*Fusarium* spp.) in winter wheat are correlated with dry springs followed by wet weather during flowering. The effects of temperature and soil moisture on *Fusarium* diseases of cereals have also been modelled using data from laboratory experiments. Different species of *Fusarium* respond in different ways and it is essential to know which type is most common in a given region and how climate affects the interaction between different pathogens in order to predict impacts of climate change on such diseases.

In winter barley, there is a strong positive correlation between incidence of brown rust (*Puccinia hordei*) and temperature from December to February. However, the effect is relatively small, with each 1°C rise in average temperature resulting in a 1.6% increase in the incidence of brown rust, leading to a 0.65% decrease in yield.

A long-term data set on the incidence of powdery mildew in sugar beet indicates a close negative relationship with the number of days of frost experienced in February and March (Figure 5.5). The incidence is expected to rise by about 27%, on average, by 2050.

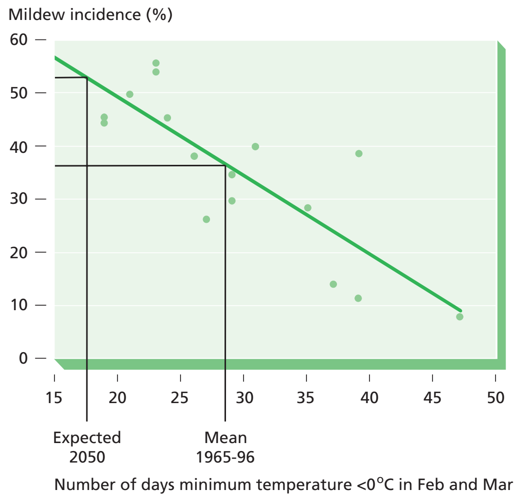

Figure 5.5: Relationship between ground frosts and incidence of powdery mildew in sugar beet at Broom's Barn.

Arable Weeds, Pests and Diseases

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Invasion of alien pests and diseases

Many non-indigenous insect species migrate naturally or are accidentally brought into the UK every year. Over 150 migrant butterfly and moth species were recorded in the UK over a 200 year period, of which 19 became established. With climate change, establishment may become more common, but it is not necessarily the case that insects that are pests elsewhere would be so in the UK. However, it is also conceivable that some insects that are not pests elsewhere, could become pests in the UK.

Perhaps the best known potential insect threat to UK agriculture is the Colorado potato beetle (*Leptinotarsa decemlineata*), which is found almost every year in potato fields but has not formed a breeding population for many years. Studies show that the area of the UK in which the beetle could survive will double with an increase in temperature of 1.8°C. In addition, the suitability of areas where establishment is currently possible will increase by 76%, making surveillance and eradication even more important and difficult than at present. Furthermore, 11% of the UK would be able to support two generations of the beetle each year, compared with 0.1% at present.

Climate change is also likely to aid the establishment of non-indigenous diseases. The prime aim should be to prevent this by stringent surveillance and eradication programmes. Some pathogens that are already encountered under glass may survive unprotected in warmer conditions.

5.3 CONCLUSIONS

Uncertainty is a key feature of predicted changes in weeds, pests and diseases. Their occurrence and prominence can depend on extreme events or a succession of events and the likelihood of these is known with much less certainty than overall changes to climate. Much remains to be discovered before it is possible to predict, with accuracy, the response of arable weeds, pests and diseases to a changing climate.

Despite the uncertainties, experimental results demonstrate that weeds can evolve very rapidly, within two years, to a changing world. Consequently, weeds may adapt to climate change and become particularly significant in years with extreme climates. For arable weeds, which mostly reproduce vegetatively (e.g. couch, bindweed or creeping buttercup), it is likely that a warmer climate will increase their rates of evolution. For those weeds that reproduce from seed, stressful conditions, rather than longer seasons, are most likely to promote rapid evolution. Some herbicide-tolerant weed strains tend to outcompete susceptible strains in warmer climates, even when herbicides are not used. Newly invading weeds are also likely to be more resistant to a spectrum of herbicides.

Many of the methods used to study the impacts of climate change on pests and diseases statistically relate climatic variables with long-term temporal and spatial data sets on pest and disease abundance and distribution. The results from such empirical studies require cautious interpretation because they are not based on a detailed understanding of the underlying mechanisms determining the relationships. Predictions from empirical models can run into trouble when future changes in climate fall outside the range of current experience.

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An alternative approach is to construct detailed mechanistic models based on field and laboratory experiments that reproduce future conditions. However, it is not possible to quantify all interactions in such models, so only those thought most important are incorporated. None of these approaches adequately account for possible adaptations of the pests or diseases themselves to slowly changing conditions.

It is not surprising that some pests and diseases are likely to increase in importance while others decrease. Even closely related organisms often have very different environmental requirements and optima. To avoid excessive chemical inputs, the development of reliable forecasting systems and control methods that protect and encourage natural enemies must be a high priority.

6. Impact of Climate Change on Grasslands and Livestock

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Livestock production systems consist of many interacting processes, most of which are influenced by the weather. This makes the assessment of the impact of climate change extremely complex.

All livestock systems are founded on crop production, even if that takes place off-farm. The changes identified above will affect livestock farming, for example through changes in forage and the price of animal feeds. Annual forage crops, such as maize, are more like arable crops in their responses. Substantial changes in rainfall and temperature would also affect soil water content throughout the year, possibly changing the period during which grazing was possible without damage to the soil structure.

The most important forage crop in the UK is grass, which is normally grown as a perennial in mixed swards. The variables likely to have the most direct effect on grass are CO_2 concentration, temperature and rainfall. Although there have been some experimental and modelling studies, the interactions between these factors are not fully understood. Grazed swards receive organic nitrogen in excreta, and the subsequent microbial and chemical processes will also be influenced by the climate. Furthermore, grass swards often include legumes, such as clover, with nitrogen-fixing microbes, which are also likely to be affected. Some of the implications for intensive grassland are discussed in section 6.1.

Semi-natural swards, such as those found on extensive upland enterprises, usually contain a diverse mixture of species. Climate change is likely to affect the competitiveness of the different species, resulting in a change in the composition (see section 6.2).

The direct impact on livestock includes thermal stress at different times of year. Many species could be at risk of heat stress if summer temperatures rise, especially those in intensive housing, where problems sometimes arise at present. Some, generally young, animals also risk cold stress, which might be diminished with a rise in temperature. The assessment of these impacts requires consideration of the metabolic heat production of animals and the modification of the climate within buildings. Experimentation at this scale is impossible, so the assessment is usually approached through simulation models (see Box 6.1). Many species also suffer from the effects of thermal stress during transport, which are likely to be exacerbated by the predicted changes in the temperature distribution across Europe. The ability of animals to adapt physiologically or behaviourally is considered in section 6.3.

Other potential effects on the health of animals come from the influence of climate on disease pathogens and insect vectors (section 6.3). A further indirect influence on the welfare of housed livestock is the possibility of increased rates of production of ammonia and other gases by microbes in slurry.

6.1 INTENSIVE GRASSLAND

Grassland is one of the most important land uses in the UK, covering more than 70% of the farmed land. The primary controls on productivity of managed grasslands are rainfall and supply of nutrients (especially nitrogen). Current management systems for cattle and sheep and their utilisation of grassland are determined by the need to grow sufficient dry matter of appropriate quality for meat, milk or wool production. The rates of feed supply are largely determined by the duration and pattern of herbage production throughout the year. In temperate climates, grass growth follows a distinct annual pattern characterised by a burst of accelerated growth that peaks in the spring and declines in autumn. This annual pattern is strongly influenced by the frequency and timing of defoliation, either by grazing animals or by harvesting for silage and hay - the means by which the farmer capitalises on the surges of growth to provide feed during winter.

The spatial and temporal interactions of soils, plants and animals in livestock systems require a farm or ecosystem approach. At present, only parts of these interactions are understood in sufficient detail, allowing only general predictions of grassland responses to climate change. Most experiments have been short-term and examined single factors. It is more difficult to extrapolate to the farm or ecosystem scale for grasslands than for monocultures producing a single annual crop. Nevertheless, information is beginning to accumulate from which it is possible to provide at least some guidance on the direction of change, if not on the rate and magnitude.

Response to elevated CO_2

The effects of elevated concentrations of CO_2 on some of the commonly used pasture species have been examined over a number of years. In general, the physiological responses are increased photosynthesis, decreased respiration, increased water-use efficiency, increased efficiency of nitrogen use, changes in flowering patterns, increased ratios of root/shoot dry matter and changes in nitrogen fixation in legumes (white clover is the species most commonly used as a test plant). However, the conclusions reached have not always been straightforward because the results often provide conflicting evidence. There has been increasing interest in using artificial swards with cutting regimes imposed (either to mimic cutting for conservation or to simulate grazing) rather than simply studying single plant responses. Such experiments demonstrate that the potential responses to CO_2 in terms of dry matter changes may be quite limited, but with longer term effects on phenology and reduced tiller numbers. Recent results have indicated an elevation of yield in response to increased CO_2 of only 8% for perennial ryegrass.

The variation in responses between plants and environments is also likely to be large. Studies in New Zealand have shown that for 37 pasture species, the increase in dry matter production with elevated CO_2 was 11 ± 21% at 12°C/7°C (day/night temperatures) and 90 ± 40% at 28°C/ 23°C. These responses varied with the stage of development of the plant.

White clover is often an important constituent of many swards: it supplies nitrogen and is thus an essential feature of organic systems. Specific effects on white clover and nitrogen fixation physiology have been recorded, but in practical terms an important finding has been an increase in its competitive ability when grown in mixed swards with elevated CO_2. This will have important implications for nitrogen supply and cycling and also for sward quality.

There is very poor understanding of the impact of elevated CO_2 concentration (and other interactive effects) under realistic grazing. The responses of plant dry matter to increased CO_2 may be altered in the presence of grazing livestock because of the continual removal of active plant tissue. There are also likely to be effects on consumption by livestock and herbage quality. The latter is important not only for grazing but also for effects on conserved diets. Increased CO_2 may enhance primary production, but is also likely to lead to changes in leaf/sheaf ratio, reduced nitrogen and increased fibre contents and, hence, an overall reduction in dietary quality. In experiments in New Zealand, higher CO_2 concentrations reduced crude protein content in white clover by 15% and in

Impact of Climate Change on Grasslands and Livestock

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perennial ryegrass by 21%. Consideration of the effects of changes in climate must therefore be extended beyond dry matter production to the implication for utilisation. Thus, although increased primary production may stimulate greater stocking rates, reduced digestibility will lead to a lower rate of liveweight gain or milk production per animal.

Effects of warmer temperatures

Large numbers of studies over many years have examined the growth responses of both single plants and swards. Although these follow classic patterns of responses shown by other plant species, they are dependent upon the age and the stage of development of the plant. This is an important consideration with a perennial crop with distinct seasonal variations in accumulation of dry matter. Wide ranges of response to temperature have been described, which is to be expected from the range of genotypes and ecotypes involved (species, varieties and other genotypic/local population differences). A range of reactions is therefore likely under field conditions, not just in terms of general growth responses but also in tolerance to chilling or heat stress.

Figure 6.1 illustrates the interactions of CO_2 and temperature during the growing season. Throughout the season, CO_2 increased dry matter (relative to the control experiment). Increased temperature is beneficial at first, but rapidly leads to a loss of biomass by the end of the season. The combined effects also changed over the duration of the growing season. Such interactions make prediction of effects complicated, especially when translated to the field scale.

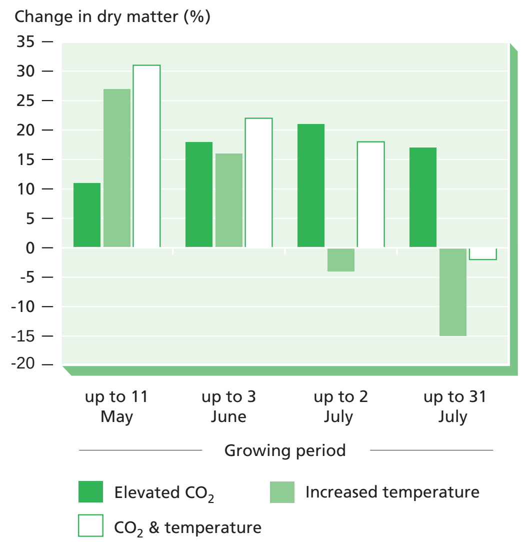

Figure 6.1: Change in above-ground biomass of *Lolium perenne* L. in response to elevated CO_2 (700 ppmv) and temperature (4°C above ambient). Source: Nijs *et al.* (1993).

Rainfall and water supply

Intensive grassland production is sensitive to water supply: either an excess or a deficit of water reduces dry matter accumulation. Small water deficits have a marked effect on leaf development and therefore on growth rate. Pasture plants in general are not well adapted, either morphologically or in terms of their overall life history, to prolonged periods of drought. Although swards can extract water to depths of up to a metre, growth is generally restricted when the soil moisture deficit in the top 30 cm exceeds 40-50 mm. On average, irrigation would currently benefit most lowland grasslands in the UK in most years.

Interactions are to be expected with elevated CO_2 concentrations. An increase in CO_2 concentration reduces water loss. The increase in root biomass that has been recorded with enhanced CO_2 concentration may also improve water relations. Together, this means that the relative growth response of plants to elevated CO_2 concentration may be greater in drought-stressed grassland than in grassland with well distributed rainfall. As with temperature, the impact of extreme years is important. Changing patterns of rainfall distribution will also have an impact.

Much grassland is currently located on poorly drained soils. A survey of 500 permanent grassland farms between 1970 and 1990 showed that 75% were imperfectly or badly drained. A reduction in excess moisture at appropriate times of the year will have obvious benefits due to an increase in trafficability, a reduction in poaching and an increase in the availability of nutrients. This benefit continues until moisture deficit is such that it reduces uptake capacity/capability. There are also implications for the loss of nitrogen to water and to the atmosphere due to changes in soil moisture. A shift to more intensive rainfall events would affect the volume and flow of runoff from grassland soils and the consequent transfer of particulate materials into surface waters. This could lead to an increased rate of transfer of nutrients such as phosphorus, with a potential increase in the eutrophication (a harmful enrichment of inorganic plant nutrients) in lakes, rivers and estuaries.

Overall effects

Assessments of the overall effects under realistic management conditions demonstrate that intensive grassland is sensitive to climate change.

Changes in temperature and rainfall are likely to reduce overall production potential. This was demonstrated in the 1995 drought, which had direct effects on the feeding regimes of livestock in lowland areas.

Model simulations suggest that climate change would extend the geographical range of forage crops, increasing the forage production potential of the north and west of England and Wales and for higher altitudes (see Figure 6.2). Scenarios for the 2020s and the 2060s are based on regional changes in temperature and precipitation for southeast and northwest England, as predicted by an early Hadley Centre model (UKTR). The models of grass growth suggest a potential enhancement in grass yields over large parts of the country, including substantial effects in western areas.

Other modelled estimates have been produced using the results of European field experiments in open-top chambers (where plants are continuously exposed to enriched CO_2 in outdoor chambers that aim to closely mimic natural conditions). These indicate that, by 2020, grass production could be 18% higher in the temperate zones of Europe due to increases in temperature. Higher CO_2 concentrations lead to a further 10-15% increase in grass production. However, a wide range of results have been obtained by different modelling studies. Furthermore, it is apparent that grassland management regimes will have to adapt to capitalise on the changes. For example, although the growing season may be extended and dry matter production increase, full exploitation of grasslands could be limited by the need to develop management strategies to overcome extended dry periods or periods of waterlogging.

Many swards contain mixtures of species. These almost certainly have differential responses to changes in temperature, moisture and CO_2 concentration. The competitive advantage of white clover when grown at elevated CO_2 concentrations could lead to a significant shift in species composition and perhaps reduce the overall requirement for nitrogen fertiliser.

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This may encourage an expansion of alternative management regimes including organic systems.

An increasingly important crop in dairy farming systems is forage maize. The temperature requirements of maize currently limit widespread cultivation to the lowland areas of southern and eastern England and coastal Wales (although it is grown as far north as Stirlingshire and Dumfrieshire). Maize has considerable implications for milk-production efficiency, nitrogen cycling and land management. The extent of forage maize production could increase northward and westward with increases in temperature, although reduced precipitation would decrease suitability in the southeast. This may introduce an element of competition between arable crops and intensive grassland/livestock production and may be a major feature of climate change. This could have major implications for the structure of agriculture in the UK.

6.2 EXTENSIVE GRASSLAND

Extensive grassland, mostly located in the uplands, provides pasture and meadows for farming, diverse habitats for wildlife and areas for recreation. Two points underlie the responses of extensive grassland to climate change. First, the majority of extensive grasslands contain complex mixtures of long-lived, often slow-growing, plants. Such vegetation has considerable inertia and is likely to respond more slowly than crops and weeds in intensive systems. Second, many extensive grasslands are already changing as a consequence of other environmental impacts. Often the task is to predict the outcome of interactions between climate change and factors such as atmospheric nitrogen deposition or the impact of management.

The impacts of the individual components of climate change give some insight into grassland responses.

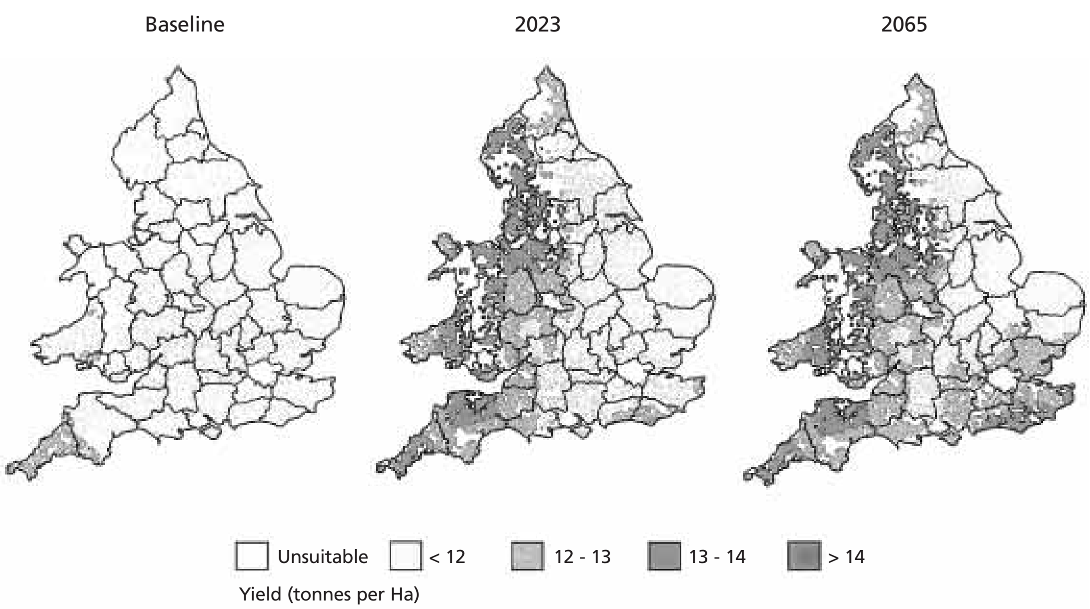

Figure 6.2: Predicted grass yield for the baseline and two scenarios of climate change from the Hadley Centre UKTR model. Source: Davies *et al.* (1977)

Response to elevated CO_2 concentration

Growth responses to elevated concentrations of CO_2 have been measured on seedlings and young plants of a wide variety of native UK crops, grassland species and weeds. In the early stages of plant development there are large differences between species in their responses to elevated CO_2 concentrations. In general, greater yields tend to occur in large, fast-growing perennials on fertile soils. Many annual weeds and slow-growing perennials on infertile soils show little or no improvement (see Chapter 5). There will be changes in the competitive balance between the dominant perennials of the most productive grasslands, heathlands and wetlands.

Among the most responsive species are some that are increasing in abundance in western Europe (such as stinging nettle, rosebay willow-herb and oat grass). In addition to changes in land use and eutrophication, a fertiliser effect of elevated CO_2 concentration could be contributing to this expansion.

Even in grassland systems of low productivity, elevated CO_2 concentrations can result in enhanced root growth and increased carbon input to the soil. Plant species appear to differ in the benefit they derive from this phenomenon. In mycorrhizal species (such as ribwort plantain *Plantago lanceolata*), the capture of mineral nutrients may be expected to increase. However, where the extra carbohydrates are released rapidly from non-mycorrhizal roots, populations of soil micro-organisms may expand, reducing the levels of mineral nutrients available to the plants.

In nitrogen-limited grassland, specific benefits of increased CO_2 concentration have been demonstrated in nitrogen-fixing species, such as white clover. In phosphorus-limited grasslands, recent experiments have detected yield increases by sedges in response to elevated CO_2 concentrations. It is suspected that the potential of species such as the sedges *Carex flacca* and *Carex panicea* to benefit from elevated CO_2 concentrations is related to the possession of dauciform (carrot-like) roots (Figure 6.3). These nodular structures may facilitate phosphorus capture. Other species, however, are limited in their capacity to respond to phosphorus stress in elevated CO_2 conditions.

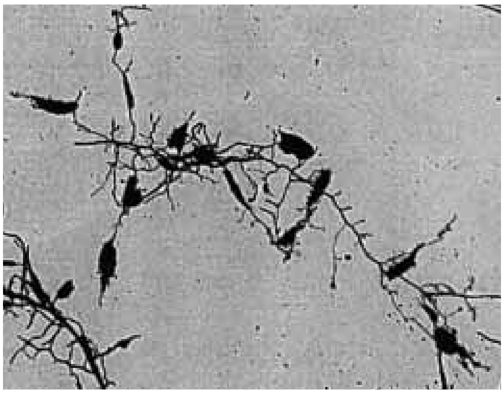

Figure 6.3: The dauciform roots of carnation sedge (*Carex flacca*). Source: P. Grime, University of Sheffield.

Water use by grassland plants is considerably reduced in elevated CO_2, thus increasing potential productivity and plant survivorship during periods of drought. Experiments have confirmed, however, that under field conditions there is a limit to the extent to which elevated CO_2 concentrations can offset the effects of moisture stress. When grassland cover and productivity is increased by fertiliser application, the greater surface area for transpiration can rapidly exhaust soil moisture reserves, even under elevated CO_2.

Further investigations will be necessary to confirm these conclusions and to detect the consequences of elevated CO_2 concentrations on soil processes, vegetation structure and dynamics.

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Effects of warmer temperatures

Laboratory experiments with seedlings show that grassland plants differ substantially in their optimum temperatures for growth. Common UK grasses such as sheep's fescue tend to have optima below 20°C, whereas those of weedy species such as fat hen and stinging nettle are considerably higher (about 25°C).

Heating of natural turf shows that plant species in extensive grassland ecosystems differ in the timing of spring growth (Figure 6.4). The timing and rate of leaf extension in the spring is related to genome size (measurable as total amount of DNA in a cell nucleus, i.e. 2C DNA content). High-DNA plants, such as rye-grass and bulbous buttercup, grow early in spring whereas low-DNA species, such as brown bent-grass and bird's-foot trefoil, delay leaf extension. With warmer temperatures, low-DNA species appear to benefit from spring warming more than high-DNA species.

Grassland plants also differ in their flowering responses to warm winters and springs. In general early-flowering species, such as spring sedge, sweet vernal grass and sheep's fescue, respond strongly to warming and are capable of flowering several weeks early in warm conditions. In contrast, species in which flowering is normally late, such as the bent grasses and autumnal hawkbit, are much less sensitive to temperature and depend upon a long daylength to initiate flowering.

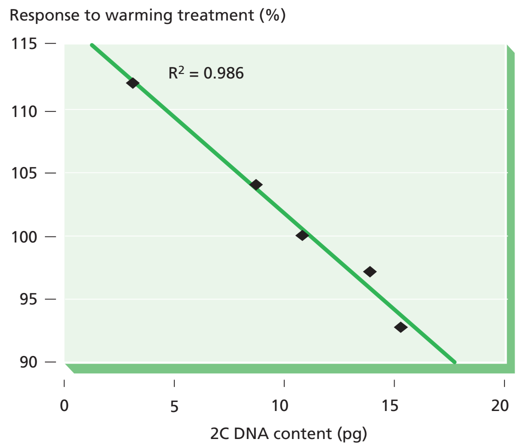

Figure 6.4: Comparison of the response to the warming treatment of five grassland species varying in nuclear DNA content. The response is calculated as the ratio of relative growth rate in warmed turf to that in control turf. Source: P Grime, University of Sheffield.

Rainfall and water supply

Four consecutive years of experiments on marginal calcareous grasslands in Buxton (North Derbyshire) and Wytham (Oxfordshire) suggest two preliminary conclusions.

- Even under the exceptionally high summer rainfall conditions and low temperatures at Buxton, summer production benefits from supplementary watering. This suggests that bent grasses and sedges could expand in importance in the event of increased precipitation, perhaps to the detriment of the deep-rooted, drought-avoiding species. Drought has little effect on the slow-growing perennials, attuned to conditions of low soil fertility.

- At Wytham, where summer drought is already a potent influence, supplementary watering treatments are beneficial but are insufficient to sustain a summer grass cover. The Wytham grasslands contain fertiliser residues from a previous management era in which cereals were

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grown on the site. As a consequence, the present grassland contains a 'weedy' and potentially fast-growing flora, which responded swiftly to severe drought. Perennial grasses declined rapidly and various annual plants (especially winter annuals) expanded.

This difference in the reaction of the two grasslands conforms closely to ecological theory. The strong inertia of the Buxton grassland is predictable from the functional attributes of the component species: long life-histories, slow growth, long-lived tissues. The rapid changes observed in the Wytham grassland are similarly predictable from the characteristics of the common species at the site: shorter life-histories, fast growth, high tissue turnover.

Implications for management of extensive grasslands

The permanent pastures and meadows that occupy most of the farmland of upland Britain contain relatively long-lived plant species with considerable potential to persist in changing climatic conditions. Nevertheless, experiments with elevated CO_2 , winter warming, supplementary watering and summer drought indicate that changes in species composition can be anticipated. This is particularly so in circumstances where soils are more fertile and plant life-histories are already short due to drought or physical disturbance by stock or farming operations. So far, no results from long-term experimental simulations of the impacts of climate changes have been reported so we must rely on extrapolations from simple models and short-term experiments.

Grassland productivity

Short-term changes in extensive grassland production have been observed in response to supplementary watering, winter heating and elevated CO_2. Sustained improvements are unlikely where low mineral nutrient supply continues to act as the ultimate limit to production. Climate improvement in the uplands may eventually justify greater use of fertilisers and encourage an extension of intensive farming to higher altitudes as more grassland is converted to intensive production with higher applications of fertiliser.

Seasonal shifts

Even if there is little overall change in productivity, it seems inevitable that alterations in species composition will occur in response to changes in temperature, moisture supply and CO_2 concentration. Lengthening of the growing season seems likely to lead to increased opportunities for grazing in winter. Increased summer drought in southern Britain would necessitate additional feeding of stock.

Palatability

Large areas of upland Britain are already colonised by relatively unpalatable plant species such as bracken, matt grass and tor grass (*Brachypodium pinnatum*). There is some evidence that plants grown at elevated CO_2 increase their carbon/nitrogen ratios, with a coincident decline in palatability to particular invertebrate herbivores. Similar changes may be expected in pasture plants, which could have detrimental effects on the nutritional value of extensive grasslands to grazing animals.
At present, we are faced with a dearth of information with which to address this important question.

Weed invasion

Annual weeds of southern distribution, such as prickly lettuce and wall barley, will have the potential to immediately spread northwards and to higher altitudes in warmer conditions. This response is related to enhanced seed production

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and dispersal in warmer years and successful seedling invasion of the patches of bare ground which become more extensive in dry, warm summers. However, these species have no mechanisms of persistence and rapidly retreat from their northern outposts during intervening cold, wet periods. As the climate warms, such species will show a rather erratic pattern of encroachment northwards. A more continuous process of spread is anticipated for southern perennials and for those annuals such as *Arabidopsis thaliana* (thale cress) where persistence through unfavourable years is possible through seed banks buried in the soil.

Experiments conducted in Derbyshire show that several weeds currently confined to southern Britain, such as perforated St John's wort and hoary ragwort, are capable of invasion and persistence if seeds are imported into northern grasslands. Here, the most striking example is tor grass, a worthless, unpalatable species that, once established, is capable of rapid local consolidation by rhizomes. It would appear that the spread of this species is currently limited by climatic restrictions on seed production.

6.3 LIVESTOCK

The growth, reproduction, behaviour and health of farm livestock are influenced both by the environment in which they live and by their genetic make-up. Climatic variations and change have direct effects on livestock appetite and health. The impacts on intensive and extensive grasslands affect nutrition. The interaction of the direct and indirect effects (through feed sources) influence animal growth, production and reproduction and ultimately the productivity and profitability of livestock enterprises.

Health

Thermal stress above a threshold related to the climate to which the animals are acclimatised increases morbidity and mortality, unless animals can initiate natural coping strategies and have access to refuges. Many of the effects of stress increase with continued exposure. The effects of heat stress are usually shown in mortality related to cardiovascular and cerebrovascular events, so they are more prevalent in older animals. Thus the effects on productive animals may be limited.

High temperatures also reduce reproductive efficiency. Exposure to high temperature from conception into early pregnancy increases embryonic death. At present it is necessary in some European countries to keep animals cool during breeding seasons, as well as at birth, to limit the mortality of offspring. In natural breeding systems, mating occurs in autumn and birth in late spring. Intensive production will have to control the timing of breeding and the environment, especially to achieve more than one breeding cycle per year.

The effects of exposure to sunshine are related to the duration and intensity of exposure and can be avoided by sheltering and behavioural changes.

Many of the effects of climatic variability on animal health are indirect. Changes in temperature, humidity and wind, especially draughts, may reduce immunity and the efficacy of vaccination. The effect of temperature stress on animals may, therefore, be exacerbated by irregular weather such as an increased frequency of storms.

Most parasites and bacteria are exotherms - their growth rates depend on temperature. Viral reproduction rates also depend on temperature when they have an intermediate exothermic host or vector. Hence, increased temperatures are

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likely to increase exposure to pathogens significantly due to enhanced pathogen survival, extended warm seasons and increased rates of development and reproduction. Exposure will also increase because of increased duration or abundance of insect vectors of pathogens. There may also be increased vector competence as viruses replicate faster.

So far, there is no evidence to suggest that many additional exotic insect vectors would survive if introduced into the UK. However, increased temperature may already be leading to a northwards spread of various species of muscid flies along with a significant increase in their abundance, and that of ticks, many of which are implicated in the transmission of disease.

It is clear that the distribution of several vectors will become restricted, as their activity is limited at higher temperatures. Pest activity will be redistributed throughout the day. Within ho using systems (such as poultry houses) breeding of vectors will probably increase, as will growth of pathogens in manure systems, requiring more effective systems to control temperature. Unless controlled, this will contribute to increased contamination of production animals with pathogens.

The level of contamination by disease pathogens (especially bacteria) partly determines the quality of food produced. There is a direct relationship between livestock contamination, temperature and food-borne diseases resulting in food poisoning in humans. More attention will have to be given to the slaughtering process, carcass handling and storage, as bacterial contamination is likely to increase under warmer conditions.

Nutrition

Animal diets vary from simple primary forages (such as grass and conserved herbage) to highly designed, processed foods aimed to achieve optimal nutrition. Local forage production depends on local climate whereas processed foods are generally produced from international sources. Climatic variations in the UK are of most importance for local feeds and for animals which obtain most or all of their nutrition from natural forage. Current systems are flexible; nutrition may be from primary grazing, buffer and total feeding of conserved forages or supplementary diets, depending on the quantity, quality and costs of feed.

In intensive grassland areas, most forage is conserved as silage or hay. Grazing is seasonally variable in its importance to diets. Changes in the seasonality of grazing affects the productivity of grassland through mechanical damage and over-exploitation.

Assuming food is available, animal intake depends on appetite, which is influenced by temperature, humidity and the palatability of the food. Changes in appetite in relation to the climate are difficult to predict, but grazing usually occurs in the morning and evening. The palatability of the food can be manipulated by the processing and formulation of diets. Adequate shelter for ruminating animals is necessary.

In extensive systems, seasonality is managed - for example, by changing the elevation of grazing. If grassland production increases, for example in the uplands, there will be more opportunity to match the production and reproduction needs of livestock when seasonal forage is abundant or scarce.

The impact of climate change on the nutrition of housed animals depends on achieving an appropriate environment to sustain appetite.

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Drinking water is the single most frequently required resource for any animal. Its provision in suitable quality and quantity may be the most important restricting factor for grazing animals, especially for dairy production. Intake varies significantly with location, especially in upland grazing areas and from contamination of natural sources. Seasonally, free water quality varies and may be affected adversely by factors as diverse as rainfall and growth of algae, which is related to temperature.

Animal adaptability

Animals adapt to their environment behaviourally and physiologically. Adaptation can be assisted or impeded by management techniques. The problems of surviving a hotter environment are exacerbated by intensive production systems. These limit behavioural and physiological adaptations and require a higher energetic output from highly productive animals. Additionally, housing systems produced for the UK are currently designed to cope with winter extremes.

In the short term, grazing animals respond to extremes of weather by seeking shelter, if it is available. Frequent or sustained bouts of extreme temperature, incident sunlight and wind require planned and maintained shelter systems. The shelter has to be available, suitable in type and size, and accessible to grazing land. Countryside management policies favour woodland systems, although these have a high water consumption in summer and may lead to increased exposure to pests and diseases.

In southern England, shelter is often provided during mid-summer by access to winter housing, as is the case for dairy cows. This system requires that the housing is accessible and that buffer feeding is given when grass growth is restricted. This is likely to impose significant additional management problems. One benefit of the system is a low sustained exposure to diseases common in winter housing.

The greatest extreme could be permanently zero-grazed herds of cattle, already the case for some dairy herds. Permanent housing introduces problems of animal density. The restricted location and increased density of housed animals increases infestation by ectoparasites (which live on the animal's body surface and breed more rapidly).

Providing shelter is already a key part of managing animals in intensive grazed systems. Further extensions will need to consider cost, planning, design and appearance. In extreme cases, systems could be designed which are similar to those used in the Mediterranean, where animals are housed in white buildings during the day, fed fresh-cut forage and put out to graze at night.

Increased capital investment in ventilation and cooling systems may be required. Some poultry producers are already installing equipment to improve internal cooling, such as reversible fans or circulation fans, which blow air across the flock to increase convective cooling. In some cases, misting systems are being introduced to produce evaporative cooling. However, these must be used with caution due to the risk of dangerous increases in humidity. Although birds hatched in warmer conditions tend to exhibit lower levels of stress, it is likely that reduced stocking or increased capital investment in cooling systems will be needed.

Behavioural changes in response to the environment have some unwanted consequences. For example, movement to cool down or avoid pests reduces feeding time. This is less of a problem for ruminants.

Physiological adaptations are secondary to behavioural adaptations. They are used when exposure to an adverse environment is more intense or sustained, as is possible with climate change. The need to regulate body temperature is a balance between heat input (increased environmental temperature and productive generation of metabolic energy), insulation systems (hair and feathers) and cooling (air temperature, windspeed, sweating, vasodilation, panting, size of animal, stocking density, etc.). Behavioural and physiological responses to cope with current short-term extremes of weather, especially higher temperatures, are mostly within the capability of production animals given a correctly managed housing environment. However, they are currently near the limits, especially for intensively housed poultry (see Box 6.1).

Outdoor cattle, sheep and poultry cope with heat by sheltering (Figure 6.5), restricting movement, sweating and using respiratory cooling. Pigs wallow as they cannot sweat. Housed animals cope by using the same methods, but the effect is limited by stocking density and housing design. With existing housing structures, the limits are already close and new designs of building are essential for the higher-producing poultry. The correct design and maintenance of outdoor pig villages is essential.

The physiological adaptation of animals can be changed in the medium term by acclimatising stock, especially during breeding (e.g. poultry bred in a hotter environment are more productive). Although genetic selection offers some promise, the current international genetic stock does not appear to offer much which is new and any genetic solution may incur a penalty of lower production.

Figure 6.5: Response of pastured cattle on a hot summer's day, seeking shade from the tree margins of a field.

Box 6.1
Simulation of grassland and livestock systems

Interactions, such as between grazing animals and the grass supply, or housed animals and the environment within the building, affect the profitability and sustainability of livestock enterprises. When subjected to climate change, some interactions may reinforce one another, while others may cancel out. Results from the ECCLIPS (Effect of Climate Change on Livestock Production Systems) simulation model illustrate the importance of interactions. The model includes:

- grass and silage production;
- animal production and feeding; metabolic heat production; balance of the animals with their environment;
- modification of the environment by buildings.

The results should be treated with caution because of the uncertainties inherent in climate change scenarios and the difficulties of modelling complex systems.

Grass-based enterprises
For all types of livestock enterprises in which grass forms a major part of the diet (sheep, dairy and some beef herds) the most important interaction is between the animals and their grass supply. The total yield of grass

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influences the overall carrying capacity of the land. The ECCLIPS simulations predicted yield increases of up to 10% for lowland clay-loam soils in both the west (Cheshire) and east (Cambridgeshire). The increase was slightly lower in the more productive western region. For poorer upland soils (Powys) the predicted yield increase was very small.

However, an increase in grass yield does not necessarily lead to an increase in milk or meat production. In the simulated enterprises, the combined effects of yield, digestibility, energy content and heat stress led to small changes in forage intake and productivity. In some cases, notably western lowland dairy cows, a greater proportion of the cows' requirements would be supplied by grass, reducing consumption of expensive concentrates. The predicted changes were small, with large seasonal variations.

In all of the enterprises simulated, the increase in heat stress was small, less than the variation between years at present. In general, large ruminants are able to tolerate a wide climatic range. This is not unexpected - similar breeds to those in the UK are found across much of Europe and beyond.

The simulation studies confirmed that heat stress was not a large problem, as livestock are usually only housed during the cooler months.

Intensive house enterprises

In many ways intensive livestock enterprises are simpler than those based on grass: clearly there is no interaction with grass production, and buildings are usually better insulated, with controlled ventilation. However, livestock are housed throughout the summer when the risk of heat stress is greatest.

Poultry are particularly vulnerable to the effects of temperature, because they tolerate a much narrower range of temperatures than ruminants. Current housing systems often have to operate close to the birds' environmental limits, so an increase in stress in a warmer climate would be expected. The simulation studies confirmed this for a typical broiler house of 480 m^2 containing 10,000 birds with a ventilation system capable of delivering 24 m^3/s (the currently recommended rate) (Table 6.1). Serious heat stress was defined as the point at which the birds were no longer able to regulate their internal temperature - potentially fatal if prolonged. In the simulations, the average total time for which birds experienced such stress increased by over 25%. This was despite a 10% increase in the energy consumption of the ventilation system.

By experimenting with the simulations, it was found that a 12% reduction in stocking density was required to reduce the risk of heat stress to current levels.

Growing pigs suffer some of the same types of problems, although less acutely. Their thermoneutral range is wider than that of of poultry, so severe stress is less of a problem. The stimulations, in which access to wallows was not provided, produced increases in stress of about 20%, with greater increases in the demand for ventilation than was found for poultry. Clearly there is a similar need for care in intensive pig production. Certainly, the importance of providing wallows will increase, and there may also be a need for additional investment in ventilation and cooling systems.

	Baseline	Climate Change
Total liveweight production (t/year)	133.7 (0.5)	133.9 (0.4)
Concentrate intake (kg/bird)	4.84 (0.0)	4.85 (0.0)
Severe stress (hours/year)	1415 (98)	1539 (91)
Fan energy (MJ/bird)	0.72 (0.0)	0.81 (0.0)
Gross margin (£/animal)	0.228 (0.0)	0.226 (0.0)

Results are shown as mean (standard deviation).

Table 6.1: Performance measures for broiler scenarios at Boxworth for present climate (baseline) and a climate change scenario.

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Transport of livestock

Both poultry and pigs are vulnerable to the effects of heat stress during transport. European legislation is now being introduced that will require adjustable ventilation on livestock vehicles used for journeys lasting over eight hours, although the requirements are currently vague. The problems are greater for UK producers because livestock are often transported to warmer climates, such as southern Europe, without time for livestock to acclimatise. Most climate simulations predict that the temperature difference between Britain and southern Europe will increase, so the risk of severe stress in UK livestock travelling south will be even greater. It seems likely that the active ventilation already required by some European countries will become more common or even mandatory, since passive ventilation has little effect when a vehicle is stationary. This will inevitably increase transport costs. For comparison, it is interesting to note that some of the southern states of the USA provide roadside fan banks for use by livestock transporters making cooling stops. Removing animals from the vehicle during rest stops is not likely to be an effective alternative to improving ventilation because activity increases their rate of heat production.

6.4 CONCLUSIONS

Grazing systems are probably able to tolerate the effects of the climate change described in Chapter 2 over the next 50 years without major problems, although substantial decrease in rainfall would be more problematic. Adaptation of the animal population by selective breeding and by acclimatisation through exposure to higher temperatures should further diminish the direct effects on the animals. Provision of shade in high summer would be beneficial.

In contrast, intensively housed livestock are at risk of greatly increased levels of heat stress under present management regimes; substantial reductions in stocking rates would be necessary. The alternative would be considerable capital investment in ventilation and cooling equipment. Equipment, such as reversible fans, circulation fans and misting systems, is already available and in use in some installations, but may not be adequate for future conditions. Alleviating heat stress during transport is likely to become increasingly important.

There is no conclusive evidence of a substantial shift in the relative suitability of regions for grassland agriculture. Changes in land use are more likely to be determined by economic factors, including changes in arable cropping.

7. Overview

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Climate change will affect agriculture in two ways. The direct effects of altered weather on crops, grass and livestock have been reviewed in Chapters 3, 4, 5 and 6. The secondary effects of global changes in markets were introduced in Chapter 2. This chapter examines the secondary effects of climate change on farm enterprises and land use, noting general strategies to prepare for climate change.

7.1 FARM MANAGEMENT

Soils, climate, markets, technology, capital and policy all influence the location and type of farming. The impact of climate change on farm enterprises cannot be determined in isolation. The role of soils and climate are noted in earlier chapters. In particular, increased climatic variability and the pattern of rainfall (amount, distribution and intensity) are extremely important in determining future cropping in a warmer climate. Unfortunately, these are the hardest features of climate change to predict. Increased climatic variability will require closer crop monitoring, scheduling of work peaks to ensure that crops are harvested and established in the appropriate conditions, and provision for greater fluctuations in markets and income.

The summer of 1995 provides an example of the difficulty of predicting the impact of climate variability (see Box 7.1). UK wheat yields were above average, despite the hot and dry summer. In contrast, yields in the hot and dry summer of 1976 were well below average. The 1995 crop benefited from sufficient winter rain that returned soil moisture levels to field capacity whereas the 1975/76 winter was exceptionally dry. As a consequence of the summer of 1995, buyers for supermarkets have increased the geographical spread (within the UK and beyond), of their sources of fresh salad crops and some fruit and vegetables.

UK agriculture is increasingly exposed to world markets. Hence, the impact of climate change on the competitiveness of UK agriculture will also depend on its impact on world production.

The impact of climate change cannot be isolated from trends in consumption. Wheat and vegetable oil consumption are increasing faster than world population as a result of economic growth and changes in diet. Red meat consumption, produced largely on grassland, is predicted to continue to fall in developed countries, but rise elsewhere in line with per capita income. More locally, warmer weather is likely to encourage the consumption of salad crops at the expense of cooked vegetables. With the possibility of growing a greater variety of vegetables, there may be less demand for traditional crops such as swedes and turnips.

Although there are current public concerns about the use of genetic modification, these and other new technologies could potentially minimise the deleterious impacts of climate change, and exploit any positive benefits. Clearly the adoption of genetically modified crops to mitigate the effects of climate change would have to be weighed against an assessment of any risks arising from their use. Much of the response by the industry to climate change will depend on plant breeders providing appropriate cultivars. Fertilisers, herbicides, fungicides and insecticides have enabled farmers to exploit suitable soils and climates, sustaining high yields and the competitiveness of UK agriculture in world markets. Climate change may shift the balance of inputs required, with implications for farm costs and competitiveness.

Any attempt to increase the rate of change in agriculture or the ability to adapt to climate change will require investment in agricultural infrastructure. The return period for capital invested on farms or in processing and marketing

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is typically 10-20 years. The patterns of investment in machinery will be affected. A significant cost of climate change will be obsolescent infrastructure.

Arable farming and horticulture

The area of combinable crops may increase in the north and west of the country as a result of a more suitable climate for their production and the reduced demand for red meat from grass.

Wheat is likely to remain a dominant crop, with higher yields, enhanced quality and rising world demand. Its dominance, in terms of crop area, may be further increased due to the introduction of fungicides that control the root diseases which restrict its production on medium and lighter soils.

There is great flexibility in the production of combinable crops, once farmers have invested in appropriate machinery and storage facilities. Farmers can introduce and switch between crops such as sunflowers, grain maize and soya beans with relative ease. However, low confidence in the forecasts of climate change will influence the speed of adoption of crops that are currently grown in central and southern France. In addition to temperature and rainfall, the timing and occurrence of spring frosts may be critical in adoption of these crops, as will their relative competitiveness compared with the gross margins obtainable from other agricultural activities.

There is likely to be an increased reliance on autumn-sown crops because of their longer growing season and to minimise the impact of summer droughts. This may result in an increase of annual grass weeds that share the same growing period (particularly black grass, *Alopecurus myosuroides*). Herbicide resistance in this weed has been confirmed on more than 750 farms.

Investment in processing factories will largely determine the location of sugar beet. The effects of any increase in summer drought may be partly offset by earlier sowing, provided that there are fewer cold nights, which vernalise this biennial crop. Earlier sowing will help to ensure the more effective use of solar radiation during the months when it is at its peak. There may be problems encountered with fulfilling quotas and poorer quality on light soils if the variability of summer rainfall increases.

Quality largely determines the profitability of potatoes. To meet the standards of the buyers, dependence on irrigation is increasing. In East Anglia, crop irrigation, mainly for potatoes, accounts for up to 20% of the daily demand in high summer. This has resulted in an increased reliance on winter storage of water. Farmers are already trying to match irrigation applications more closely to crop requirements; further measures will be adopted to ensure the best use of limited supplies. Refrigerated storage of potatoes may increase, due to warmer winters and concern over the use of chemical sprout suppressants. Investment in refrigeration, machinery and irrigation will hinder movement of production to new areas that might become suitable with climate change. There may also be a shift from main-crop potatoes to early ones.

The high temperatures in July/August 1995 illustrate some of the problems of climate change for horticulture (see Box 7.1). Crop schedules were interrupted, as harvest and sowing dates were closer together than normal. Some crops were abandoned when they became over-mature. Some crops were harvested at night to ensure they reached end-users in good condition. Such problems could be offset with the use of varieties with a greater range of maturity.

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There may be long-term implications of climate change for permanent crops, where plant spacing and layout may have to change to optimise production.

Climate change may result in an increased emphasis on production of protected crops in temporary structures rather than in glasshouses. This is partly because heating and CO_2 enrichment will become less necessary.

Specific adaptive options for crops include:

- new crop varieties with genetic adaptation, including selective breeding from crops adapted to similar conditions worldwide to increase the sink capacity for extra carbohydrates;
- delayed maturity and maintenance or extension of the growing period under warmer conditions;
- drought-resistant varieties;
- agronomic adaptation to optimise production in changing conditions;
- shifting crops to areas with the best conditions for efficient production;
- dynamic management of crops to optimise timing and rates of treatment;
- introduction of new crops;
- adoption of the most effective methods, especially in irrigation and nutrient application.

Livestock production

Animals and livestock enterprises are highly adaptable - they already comprise a broad range of management in order to accommodate local climatic extremes in the production of milk, meat, wool and other products. Livestock enterprises are versatile and will be able to react in a positive way to change.

Livestock can be helped to acclimatise to climate change by suitable management. Stocking densities can be reduced and ventilation systems improved. More rigorous controls on carcass processing may be required. A limited breeding input may be necessary. Many lessons can be learnt from productive systems in warmer climates. The key to acclimatisation by livestock in extensive management systems will be availability of water. In the long term, adaptation has implications for the appearance of the countryside.

In the short term, fodder maize is likely to become more important and extend its geographical range. This will have implications for the structure of livestock management in the UK and also for the environment.

Production from lowland grassland may increase as a result of climate change. This may help the competitiveness of UK livestock. However, the projected longer growing season and the possible increase in variability of the climate could pose additional burdens on costs and management, with farmers having to cope with large variations in grass production within and between years. There may be increased reliance, at times, on supplementary feed (including either purchased or stored forage) and there could be a large variation between years on the demand for cereal straw from the major arable areas. Short-term grass shortages may bring forward sales of livestock or, where there is regional variation in grass supply, may result in an increased movement of livestock.

Production from grasslands in upland areas, however, may not increase significantly with climate change. Hence, climate change may be less important in these areas, although increased temperatures are likely to result in drier soils which could exacerbate upland erosion problems.

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Provision of shade and water will be of increased prominence for all livestock. However, it is unlikely to become hot enough for dairy cattle always to be housed during the day in summer and only to graze at night, as is the practice in some countries.

The likely increase in the variability of grass growth between and within years, plus the impact of warmer summers, may change seasonal production of milk and red meat.

The hot summer of 1995 indicated that increased temperatures reduce food intake and productivity of indoor pigs and poultry. This may be partly offset by improved ventilation and cooling and by reduced stocking rates through earlier slaughter dates. Such changes may be warranted to reduce concerns over animal welfare.

7.2 LAND USE

The implications of climate change for land use in the UK are important, but uncertain. Changes in land use will be driven by shifts in farm enterprises, as noted above. Perhaps the clearest conclusion is that greater diversity of enterprises will be possible in most of the UK. Temperate crops suitable in warmer climates, such as sunflower, maize and grapes, will expand. Livestock based on extensive grazing may shift to more intensive production.

Climate change will affect every natural resource and sector of the economy. The interactions between sectors may be more telling than the direct effects. For example, irrigation in East Anglia depends on the availability of water, which depends on changes in land cover, rise in sea level and intrusion of salt water, and consumer demand for water. The demand for municipal and household water may increase with warmer temperatures, as happens during hot summers when lawns and gardens are irrigated. Longer summers and milder winters would increase the use of the countryside for recreation. This would increase the demand for natural areas and water-related activities, providing both opportunities and problems for farmers.

Natural flora and fauna will also be affected by climate change. Since agriculture covers much of the UK, it is important that farmers consider what they might do to lessen the impact on wildlife. For example, beetle banks and uncultivated land may provide refuges and migration corridors for vulnerable species.

Managing the changing landscape will increasingly be a concern for the diverse interests in the countryside. Conservation agencies may need to evaluate which species and habitats need protection in their present locales and which can migrate with the new climates.

7.3 CONCLUSIONS

The impact of climate change depends on the mix of global effects on demand and production - the competitive market in which the UK operates - and the local effects of warmer temperatures and altered growing conditions. The policy and economic framework for European agriculture could significantly mitigate the impact of climate change; indeed, it is essential to ensure future adaptation to new climatic opportunities as well as constraints.

The agricultural industry in the UK is highly adaptable, as demonstrated by the use of improved technology, and the sustained output and profitability over the last 50 years. The ability to manage the transition to new climates, markets and technology requires foresight to

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monitor climate and its impacts, to maintain viable agricultural enterprises, and to integrate agricultural and environmental objectives.

Significant uncertainties remain in our understanding of climate change, its impacts on crops and livestock, and the most effective responses. Nevertheless, farmers are accustomed to uncertainty and to managing variable resources.

Three strategies to prepare for climate change should be considered.

- First, and foremost, adaptability to change needs to be enhanced. Government, levy bodies boards, extension services, farmer co-operatives and organisations, and farmers themselves should promote the adaptive capacity of UK agriculture in a changing world. Monitoring and learning about climate change and its impacts will provide an understanding of the issues and a basis for timely action when warranted. Further research has a role; long-term databases, monitoring networks, experimental trials and development of crop-climate models are all important. Adaptability in the face of climatic hazards - drought, windstorms, floods and intense rainfall - is a present need that may be essential to cope with future climate change.

- Second, climate change should be anticipated in some decisions. For example, investment in new irrigation systems should consider the likelihood of decreased supplies, greater demand and the benefits of more efficient water use. Real-time climate monitoring and decision support systems are already available. Over the next few years, seasonal climate forecasts may improve considerably. Farmers should take advantage of such climate information to decide which crops to grow, to tune the crop calendar and to enhance yields and quality.

- Third, international agreements to limit greenhouse gas emissions will affect UK agriculture. Although this is not the main topic of this booklet, agriculturists should consider taking steps to reduce emissions of methane, nitrous oxide and CO_2.

Climate change, its impacts and effective responses are complex issues, with a great array of interactions within and between natural and semi-natural ecosystems, managed fields, farm enterprises and other sectors. Assessments, such as the one presented in this booklet, must be reviewed and updated. Present predictions may need to be revised as new information becomes available.

Box 7.1
The hot summer of 1995

Hot weather, such as the summer of 1995, is likely to become more frequent in the future. Even with the range of climate change anticipated in the next few decades, if climate change predictions are correct, 1995 would still be exceptional. The impacts of the 1995 summer and, perhaps more importantly, how farmers coped provide some indications for adapting to future climate change.

In general, the weather in 1995 was good for cereals and bad for root crops and livestock. The year started with a wet winter and a cool dry spring and then the long, hot and dry summer that everyone remembers. The early autumn was moist and warm, which helped perennial crops like grass to recover. Likewise, the previous wet winter and cool spring helped to buffer crops against the worst of the heat and drought. A dry winter and more usual spring temperatures would have given rise to far worse problems during the summer.

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Cereal yields and quality were good. The protein content of grain rose, which was good for bread-making wheat but not for malting barley. The harvest was large and early, allowing farmers to make a cost saving with fewer working days and less grain drying, but this was probably matched by increased costs for seed-bed preparation in the autumn.

Pulses, such as peas and beans, suffered quality and yield losses due to the drought. Sugar beet and potatoes, in common with most root crops, grew poorly and had more quality problems in the heat and drought. Irrigated potatoes that produced the quality required by the markets claimed a high price. Many farmers are now investing in irrigation equipment in case we have another hot dry summer.

Disease levels were lower overall, although powdery mildew was a problem in some crops. On the other hand, insect populations, especially aphids, flourished. The low soil water supply meant some crops had severe competition from weeds for what water there was and many pesticides had limited activity in dry conditions.

Farmers coped with the conditions by spraying and irrigating in the evening or at night. The early short harvest period also resulted in long days and antisocial working hours. The continuity of supply for vegetables and top fruit was disrupted. If such summers become frequent, buyers might turn to more imports to ensure supplies.

Cattle enterprises suffered because of a shortage of grass and forage, although upland forage for beef was less restricted. Many areas could only take one silage cut, and grass production in the driest areas dropped by 20-30%. Maize yields were down by 30%, and other feeds such as potatoes were in short supply. All this resulted in food supply problems over the winter, with farmers buying in feed or selling off animals. One beneficial effect of the summer was that, although hay and forage prices were high, cereals had produced a lot of good quality straw, which some farmers used to supplement rations. Dairy cattle had reduced milk yields. Conception rates in dairy and beef were 5% lower during the summer. It is difficult to know whether cattle suffered from heat stress or whether decreased production was due to fodder, drinking water and disease problems.

Sheep also suffered from forage supply and heat problems, and supplementary grass feeding was often necessary. Increased numbers were slaughtered as the summer wore on, reducing the market price. Pigs and poultry both responded to the heat by reducing feed intake. This resulted in lower slaughter weights for pigs and reduced egg-laying, low broiler growth rates and increased mortality in poultry.

Sources: Report to MAFF by ADAS (contact: Mr J.H. Orson), summarised from the *Environment Protection Division R&D Newsletter* No.1 (January 1997), www.maff.gov.uk/environ/epdnews1/epdnews2.

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