Centre for Agricultural Strategy

The 'greenhouse effect' and UK agriculture

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2 The potential impact on agriculture of the 'greenhouse effect'

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INTRODUCTION

This paper first considers the array of methods currently used to assess the likely effects of climatic changes on agriculture. It then outlines the range of possible effects on agriculture in various parts of the World, before proceeding to consider likely impacts in the UK. It concludes with a summary of the changes in technology and policy that may comprise appropriate responses, either to mitigate the negative effects of climate change or take advantage of the positive ones.

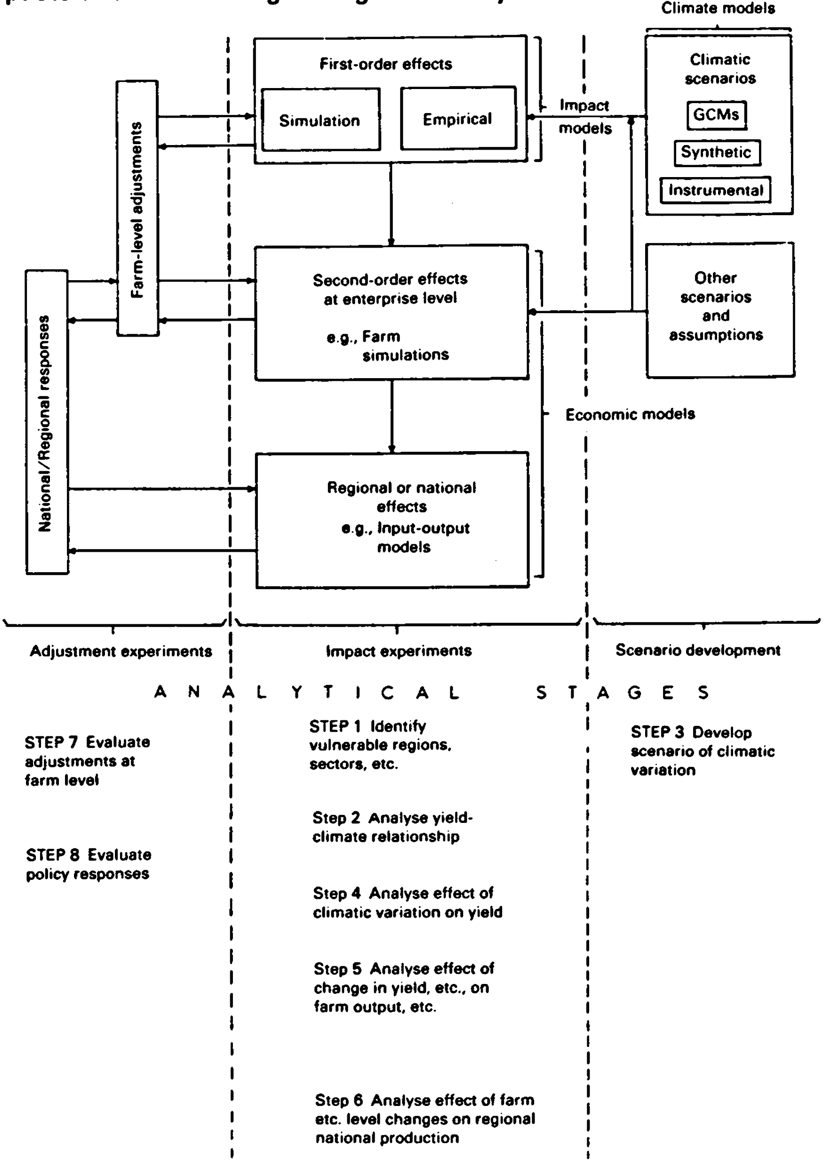
METHODS OF IMPACT ASSESSMENT

Models

The most widely used approach in the assessment of impacts of climatic change is one that employs a hierarchy of models (see Figure 1). At the top of the hierarchy are models or 'scenarios' of climatic variation. These are used as inputs to biophysical models of first-order relationships (ie those between certain climatic variables and biophysical supply or demand). Outputs from these (for example, in the form of altered crop yields or yield probabilities) are used as inputs to economic models of second-order relationships at the enterprise level. These consider the effects, for example, of changes in farm-level production on farm incomes, farm purchases, etc. As a further step, economic models of higher-order relationships (for instance, those between farm profitability and regional employment or gross domestic product) can be employed to evaluate effects elsewhere in a region. This was the approach followed by the International Institute for Applied Systems

Figure 1

Types of model used and stages of analysis in the assessment of the impacts of climate change on agriculture by IIASA



Source: Parry & Carter (1988).

Analysis (IIASA) in its case studies of impacts on agriculture (Parry *et al*, 1988a & 1988b). Ideally the effects of climatic variations are analysed in terms of their interactions with other physical systems, distinguishing between those in which the effects of a climatic variation are transmitted through other physical systems (eg by changes in soil structure, soil nutrients and soil erosion; by pests and diseases, etc), and those in which the effects of a climatic variation are themselves affected by other concurrent environmental trends such as groundwater pollution, soil nutrient depletion and so on.

Recent studies, such as that by IIASA and the US Environmental Protection Agency (EPA, 1988), have distinguished between, and tested, two types of response to climate impacts:

(i) adjustments at the enterprise level (which at the farm level might include changes of crops, increased irrigation, changes in fertilization, etc) and
(ii) policy responses at the regional, national and international level (see Figure 1).

Direct and adjoint methods

The scientific method most commonly adopted in climate impact assessment is the *direct method*, in which the analysis proceeds in a number of steps from a given climatic change to the estimated impacts (eg change in temperature ⇒ change in crop biomass productivity ⇒ change in forage level ⇒ change in carrying capacity ⇒ change in livestock production ⇒ change in meat and milk supply, etc). The analysis is thus conducted on the basis of the character of the climatic changes rather than their likely impacts. However, given the present uncertainties about changes of climate, particularly at the regional level, agricultural impact assessments have tended to adopt an alternative or *adjoint method*, considering first the varying sensitivities of different regions, sectors and farming systems to different types of climatic variation and thus identifying, *a priori*, points of especial vulnerability that should be the focus for study. The steps are illustrated in Figure 1. An advantage of this approach is that it can help identify sensitivities independently of state-of-the-art projections of future climate, employing a range of plausible scenarios both climatic and non-climatic in origin (Parry & Carter, 1984).

Climatic scenarios

Three methods have been used to characterise the altered climates expected under higher concentrations of greenhouse gases. Most widely used are the results of experiments with atmospheric general circulation models (GCMs), commonly for an equivalent doubling of atmospheric concentrations of CO_2. Some studies have made use of historical analogues of warmer conditions (such as the 1930s warm and dry period on the North

American Great Plains). Finally, it is possible to develop synthetic scenarios of possible future climates by adopting combinations of arbitrary changes in climatic variables (such as +1 and +2°C, +10% and −10% precipitation).

In the summary that follows the effects considered are those expected under climates simulated by GCMs for an equivalent 2 x CO_2 forcing. Five GCMs have been used, to date, in 2 x CO_2 experiments. There are quite wide differences between them in the magnitude of changes in temperature and precipitation but, more importantly for agriculture, there is very little agreement on the likely changes in regional patterns of precipitation.

TYPES OF EFFECT ON AGRICULTURE

To date, only three comprehensive assessments of the consequences of climate change for agriculture have been completed at the regional and national scale, and there has been none at the global level. National assessments have been undertaken in the US and Canada, and international regional case studies have been carried out by IIASA for the UN Environment Programme (EPA, 1988; Environment Canada, 1987; Parry *et al*, 1988a & 1988b). A number of countries have completed reviews of existing knowledge, as opposed to initiating new research, including the UK, Australia and New Zealand (DOE, 1988; Pearman 1988; J M Salinger, personal communication). The following is a summary of the types of effect on agriculture that emerge from these studies, rather than a description of them for each region.

It is useful to distinguish between two broad types of effect on agriculture – the fertilizing effect that increased atmospheric CO2 may have on plant growth, and the effect of changes in weather on crops, livestock, diseases, pests, weeds and soils.

The fertilizing effect of increased CO_2

Carbon dioxide in the atmosphere can enhance plant growth in a number of ways. It can increase the rate of photosynthesis, leading to greater leaf expansion and a larger canopy, and it can reduce water losses from crop plants - a beneficial effect where drought is a problem.

The effects are much more pronounced, however, in some crops than others. C3 crops, such as wheat, barley, rice and potatoes, respond vigorously to CO_2 enhancement. But C4 crops, such as maize, sorghum and sugar cane, do not. Crops in central and northern Europe thus stand to gain, although the outlook is not so good in much of Africa where maize, sorghum, sugar cane and millet are staple crops.

In addition, it should be noted that in north-west Europe the more troublesome weeds for arable farming are all C3 species and should benefit from CO_2 enhancement. Although little experimental evidence is available, it is likely that they could become more troublesome if C4 crops such as maize are cultivated widely.

More research is needed before we can say how much yield increase will occur in crops, but for a doubling of CO_2 it could be as much as 40% for wheat and barley (Cure, 1985). This figure should be approximately halved for effects that might occur by about 2030 (the estimated time at which increases in greenhouse gases would have an effect equivalent to a doubling of CO_2), because increases in CO_2 account for only about half of estimated greenhouse-gas forcing. There are also some negative aspects to the 'direct' effects of CO_2 – the food quality of plants tends to deteriorate as carbon dioxide levels increase. Leaves become richer in carbon and poorer in nitrogen. Pests feeding off these leaves may thus need to consume more to gain their required nitrogen nutrient levels (Oechel & Strain, 1985). Moreover, if plants grow more quickly they may need more fertilizer, and if rainfall increases while plants require less moisture, that might mean more run-off, more erosion of the soil and more leaching-out of soil nutrients.

Effects of changes in weather

The effects through changes of climate and weather are less easy to determine because they will continue to vary greatly from year to year and from region to region, and there is great uncertainty about these future temporal and spatial patterns of climate. Because of this, most current estimates are for average (equilibrium) conditions that might prevail under an increase in greenhouse gases equivalent to a doubling of atmospheric CO_2. The following summary considers, initially, first-order (biophysical) impacts and, secondly, higher-order effects on the economy.

First-order effects

(i) *Changes in length of growing season and period of crop growth.* Two of the major implications of CO_2-induced temperature changes for the growth of agricultural crops at present cultivated in cool temperate and cold regions are, first, a lengthening of the potential growing season and, second, an increase in plant growth rates and thus a shortening of the required growing period. For example, in southern Saskatchewan under the 2 x CO_2 scenario developed by the Goddard Institute for Space Studies (GISS) GCM, with mean May-August temperatures increased by about 3.5°C, the growing season is lengthened by 4-9 weeks, while the estimated maturation period for current varieties of spring wheat is reduced by 4-14 days (Williams *et al*, 1988). Broadly similar increases in the growing season are indicated for similar high-latitude locations, such as Scandinavia, central USSR and northern Japan (Parry *et al*, 1988) implying increases in production potential in the regions.

At lower latitudes, particularly where growing seasons are determined by rainfall, it is much less clear what the consequences may be. There are some indications that rainfall may decrease in the Mediterranean region, the southern US and in some other semi-arid regions, which would, *ceteris paribus,* lead to shortened crop growing seasons (EPA, 1988; Jager, 1988).

(ii) *Changes in mean crop yield.*

In cool temperate and cold regions yields of most crops can be expected to increase with increasing temperature, except where moisture is a limiting factor. Under these conditions the low-temperature constraints on achieving potential yields are reduced. However, the temperature increases estimated at high latitudes are in some cases so great that existing, often quick-maturing, crop cultivars are ill-adapted to the longer and more intense growing season and to the variability about the higher mean temperatures. As a result, mean yield levels indicated by recent studies are usually no greater (and frequently lower) than those obtained during anomalously warm periods at the present day (Parry & Carter, 1988).

Some crops can be expected to perform better than others. For example, under the 2 x CO_2 GISS scenario, winter wheat would probably give higher yields than spring cereals in Saskatchewan (Williams *et al,* 1988) and in the central (Moscow) region of the USSR. Also, in the latter region, crops with greater thermal requirements such as maize would show a greater increase in yield than cool-region crops such as potatoes and oats (Pitovranov *et al,* 1988). The differences in yield between various crops can thus be expected to alter. This will affect the relative profitability of different crops and thus the extent to which they are grown in different regions.

In the United States, there are indications of decreases in yields of wheat, maize and soya under a 2 x CO_2 climate (EPA, 1988). For wheat, these decreases may be partly compensated by the direct, fertilizing effect of CO_2. Overall, however, there are significant decreases in the productive potential of staple food grains under the 2 x CO_2 climatic scenarios derived from a variety of GCM experiments.

In Australia, yields of winter wheat may be reduced if there is a decrease in winter rainfall, particularly in marginal growing areas such as the south-west of Western Australia (Pearman, 1988).

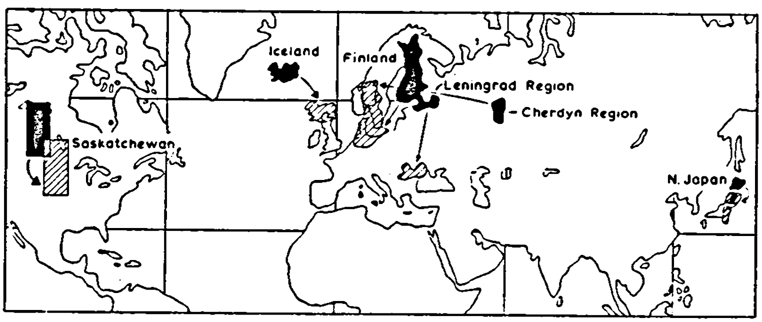
(iii) *Spatial shifts of agricultural potential.*

The changes in agricultural potential described in the preceding pages imply that climatic change is likely to bring about a spatial shift of crop potential. Areas which are, under present climatic conditions, judged to be most suited to a given crop or combination of crops or to a specified level of management will change location. In its simplest form this kind of shift can be seen as a shift in limits of the cultivable area. For example, large-scale climate-related shifts of potential for maize and wheat have been investigated in North America (Blasing & Solomon, 1983; Rosenzweig, 1985).

One potentially useful method of interpreting future climatic scenarios and their likely impact is to identify *analogue regions*, which have a present-day climate that is analogous to the future climate estimated for a study area. Analogue regions of this kind are shown in Figure 2, based upon changes in temperature and precipitation assumed under the GISS 2 x CO_2 scenario. Note that the figure was constructed using information from only one or two meterological stations in each case study area, and is designed merely to be illustrative.

This analogue approach is useful in illustrating the magnitude of climatic change within a region in terms of the present-day differences between regions. For example, Iceland's climate under the GISS 2 x CO_2 scenario is similar to the climate of northern Britain today. Moreover, the present-day farming types in analogue regions are a useful indicator of the adaptive strategies likely to be required to re-tune agriculture to altered climatic resources. For example, rice varieties at present grown in central Japan, which was identified as an appropriate regional analogue for the GISS 2 x CO_2 scenario in northern Japan (Hokkaido) were used in adjustment experiments with crop simulations for Hokkaido to evaluate their adoption as an appropriate adaptive response (Yoshino *et al*, 1988).

Figure 2
Present-day regional analogues of the GISS 2 x CO_2 climate



Source: Derived from Parry & Carter (1988).

Higher-order effects of climatic variations on agriculture

Several types of higher-order effect at the farm, regional and national level arise directly from the first-order effects summarised above.

(i) *Effects on farm profitability.*

These are difficult to assess because their estimation assumes a knowledge of any change in the costs of inputs (see Ketturen *et al,* 1988 and Williams *et al,* 1988 for examples of such assessments in Finland and Saskatchewan respectively).

(ii) *Effects on regional production costs.*
Changes of yield may also affect production costs,particularly in centrally-planned economies where regional production targets are fixed and where levels of input are often adjusted to counter weather-related variations of yield (see Pitovranov *et al,* 1988).

(iii) *Effects on regional and national food production.*
As yields are altered by differing amounts according to crop type, soil type, level of input and type of management, the aggregate effect on regional or national food production is not easy to evaluate. As a result, it has thus far been possible only to provide model-based estimates for single crops (eg Williams *et al,* 1988; Yoshino *et al,* 1988).

Few generalisations can yet be made about likely effects on global food supply. However, it is quite possible that warming will increase output potential at high latitudes in the northern hemisphere – in regions where current farm output is encouraged by heavy state subsidies. Without large-scale reductions in this support, it is likely that surplus production would increase in these areas under a warmer climate.

Overall, it is quite possible that climatic change could alter the geographical pattern of main producing regions to the world food market. It is not possible at present, however, to say how this pattern might change, except that (in the most general sense) warming may enhance agricultural potential in high latitude and mid-latitude maritime regions and reduce potential in mid- and low-latitude continental regions. There have been estimates that, worldwide, average agricultural production costs could increase by 10–20% (Schelling, 1983), though this has been disputed (Crosson, 1989).

POTENTIAL IMPACTS IN THE UK

At the level of the UK, only the most generalised changes can reasonably be estimated, and even these are unclear. In the absence of more precise information it may be reasonable, for the present, to assume that changes in average annual temperatures in the UK will broadly follow those best estimates of changes in global average temperatures. Estimations for greenhouse-gas emissions that are assumed to continue to increase along their present path, suggest an increase of about 0.5°C by 2000–2010, about 1.5°C by 2020–2050 and about 3°C by 2050–2100+, with warming in the UK possibly more pronounced in winter than summer. These estimates have been made by the Climatic Research Unit at the University of East Anglia (Wigley, 1989). The ranges in the timing of temperature increases given here reflect uncertainties about how the climate will actually respond.

Possible changes in rainfall in the UK are much less clear. In the south and east there may be less summer rainfall and more winter rainfall, while in the north and west, both winter and summer rainfall could increase (DOE, 1988). There is a possibility that, with higher temperatures, rainfall may be more in the form of convective thunderstorms.

Though we should not be complacent, particularly with the high degree of remaining uncertainty, the implications of these climatic changes for the UK do not seem as dramatic as for some other parts of the World, and are in many respects ones that offer opportunities to UK agriculture.

Effects from sea-level rise

Recent estimates of sea-level rises of as much as 7 m are probably greatly exaggerated. The present scientific consensus is around 0.2 m to 1.5 m by about 2030 (Jager, 1988). However, it may still cost the UK in the region of £5 000 M in new sea defences to protect against high tides and storm surges acting at the higher mean sea levels – and this would not protect against a rise in fresh groundwater levels, which could waterlog low-lying soils (Boorman *et al*, 1988). There is also the possibility of intrusion of saltwater into groundwater in coastal regions, and of saltwater backing up rivers and estuaries, both of which could reduce the availability of water for irrigation.

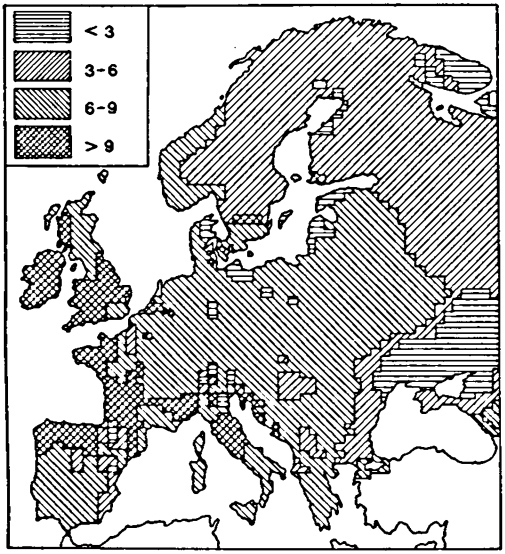
In general, the effects of sea-level rise on UK agriculture seem to be negative. But at least the expected rise will be roughly constant over the next few decades, and at a rate (probably about 10 – 15 cm per decade) that should allow time to devise means of minimising the damage. It is the potential effect of climate on UK agriculture that is likely to be either more damaging or more beneficial for UK farmers.

Effects from climate

Let us consider first the changes in *potential* for farming. The growing period could lengthen in northern Europe if average temperatures increased. Under a climate predicted by the UK Meterological Office GCM for an equivalent doubling of CO_2, the number of months with average temperatures above 5°C and rainfall exceeding half of potential evapotranspiration would exceed 9 throughout the UK, save for the extreme south-east, where the growing season in the future might be interrupted by moisture shortage during the summer (Figures 3 and 4). Yet in the Mediterranean, the growing season could shorten significantly due to warmer and drier conditions in spring and autumn. Seen in these simple terms, there is a shift of cropping potential from southern EC countries to northern EC countries.

Higher temperatures also imply that crops which are at present near their northern limit of cold tolerance in the UK would benefit, providing moisture remained in sufficient supply. Thus the temperature limit for the successful ripening of grain maize, which at present lies in the extreme south of England, would be re-located across central England with an average warming of 0.5°C, across northern England for +1.5°C and across northern Scotland for +3°C (Figure 5a). This is an average location for an average warmer climate, and is based on temperatures adjusted to sea level. Year-to-year variations could still be expected to occur around this average, just as they do now. For example, the temperature limit for maize in the summer of 1976 lay well north of its present normal position.

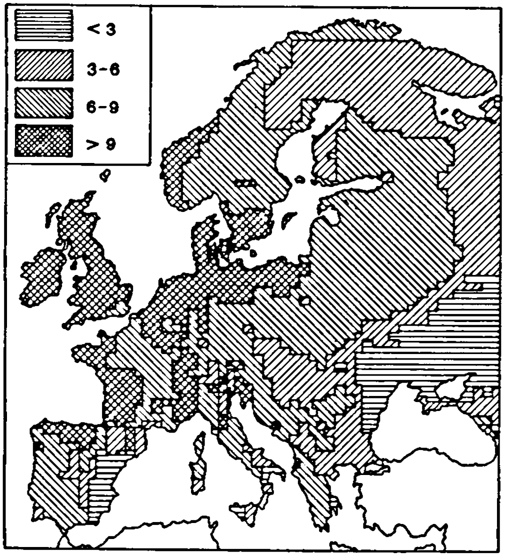
Figure 3
Length of growing period (months) under the present-day (1931–60) climate



Source: Derived from Brouwer (1988).

Figure 4

Length of growing period (months) under the climate simulated by the UK Meterological Office GCM for a doubling of atmospheric CO_2 concentration



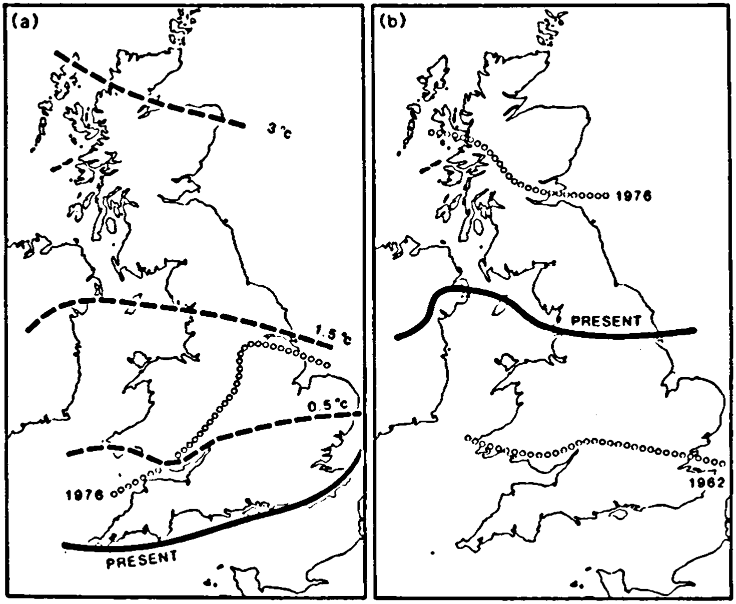
Source: Derived from Brouwer (1988).

The corresponding limit for silage maize can also be mapped according to its temperature requirements (Figure 5b). These are less demanding than those for grain maize, thus defining a present-day boundary across the (cooler) north of England. Again, the year-to-year variations around this average can be quite significant, illustrated here by the contrast between a warm year (1976) and a cool year (1962). Indeed, the scale of shift of such limits from the warmest to the coolest years in the past 30 years, is broadly similar to that expected to occur under a 2 to 3°C warming. Any future warmer climate would also have embedded within it the year-to-year variations of growing season that we experience now, but whether the range of these variations will be similar to the range experienced today is uncertain. This temperature limitation is, of course, only one of several limitations placed on maize growing in the UK.

The pattern of rainfall is also likely to change and while temperature and rainfall may alter, daylength (which is also important) will not. Several crops are constrained in the UK as much by lack of sunshine and by quite high levels of air humidity as by temperature. Sunflowers, for example, are restricted at present to the extreme south of England, and even here there is a problem of mildew before the seedhead is fully ripe. But whatever remain

Figure 5

Hypothetical limits for successful ripening of (a) grain maize and (b) silage maize, based on temperature[1]



1 Grain maize requirement: 850 degree days above a base temperature of 10°C.
Silage maize requirement: 1460 degree days above a base temperature of 6°C.
Mean limits (solid lines) are representative of lowland conditions, based on temperature data from 78 stations for the period 1951–80. Limits for individual years (open circles) and for adjustments in mean temperature (broken lines) are also shown.

the other constraints on sunflower growth, their temperature limit may be re-located about 500 km further north under a climate that is 1.5°C warmer than it is at present. In summary it seems that such limits of temperature shift about 300 km northwards in the UK for each 1°C rise in mean annual temperature.

Whether a northward shift of crops will actually occur is a matter of how agriculture might respond to changes in potential, and that will be discussed later. But it remains a possibility that, if farmers respond simply to changes in climate, fields of grain maize and sunflowers (which are a common sight in France not more than 100 km south of the English Channel) could be a feature of southern England in the future.

However, while higher temperatures might extend the potential range of crops in the UK, they would tend to decrease yields of some crops in the present core production areas. For example, yields of current varieties of winter wheat in south-east England might be expected to decrease in the absence of CO_2 fertilization, and the positive effects of CO_2 could be cancelled out by temperature increases of above 4°C (Squire & Unsworth, 1988).

Much would depend on changes in rainfall in the UK, not only in the annual average amount but in its distribution throughout the year, and we know little about how this might change. However, we do know that relatively small changes in rainfall could affect the map of types of farming quite substantially. To illustrate, the broad distinction between the arable east and pastoral west of England partly stems from differences in rainfall receipt between east and west. Very approximately the line of 780 mm per year divides the regions having more or less than 40% of farmland under cereals (Davidson & Sturgess, 1978). A 20% decrease in annual rainfall, with the same seasonal pattern and regional distribution as now, would shift that 780 mm line up to 100 km westwards. Would that imply a westward extension of arable farming? Conversely, would an increase in rainfall lead to an eastward shift of land-use belts? The reality of this situation would be greatly complicated by other effects, for example by effects on the availability of water for irrigation in the east and on the existing market for meat and cereals. But the suggestion is that quite small changes in climate could substantially alter the pattern of agricultural potential. Again, we should stress that how UK farmers respond to such changes in potential is wholly another matter.

What of the possible changes in the uplands of Britain? A 3°C rise in temperature implies a rise in the potential limit to cultivation of about 500 m (1640 ft) (Squire & Unsworth, 1988). Thus where excessive rainfall and exposure did not continue to restrict farming, there might be increased opportunity for cropping in the uplands. Probably more important would be the extension of the grazing season by one or two weeks in both spring and autumn, making it more profitable to improve and maintain upland grassland, and higher temperatures could reduce the tendency for sedge and other rough grasses to invade improved land, making it easier to maintain. No figures are yet available for the increases in carrying capacity in the UK uplands, but recent work in Iceland indicates that, under a 2 x CO_2 warming of 4°C, the carrying capacity of improved grassland for sheep increases three and a half times and of unimproved rangeland increases two-thirds (Bergthorsson *et al*, 1988).

In reality, the future of agriculture in the UK will depend very much on changes elsewhere, particularly in the present breadbasket areas of the World. There are indications that higher temperatures and reduced moisture on the US Great Plains and the Canadian prairies, as a result of greenhouse warming, could significantly reduce production potential in North America. We should not rule out the possibility, then, of northern and central Europe increasing its role as a producer to the world food market.

Effects on water, soils, diseases and pests

Before considering the responses that farmers might make to these changes in potential, it is important to consider the concurrent effects that changes in climate will have indirectly on crops and livestock, through changes in water for irrigation, changes in soils, and changes in the rate of losses to diseases, pests and weeds.

In south-east England, in order to offset increased evapotranspiration under a 3°C warming, it is estimated that rainfall would need to increase by 10% if shortage of water for use in agriculture were to be avoided (Beran & Arnell, 1989). The increased costs of water that might result could affect the amount of water not only used in irrigation, but also in spraying and in washing fruit and vegetables. The cost of construction of irrigation systems (in the order of £1 000–£3 000 per hectare) could be one factor encouraging the westward and northward shift of cropping patterns. Reduced run-off in dry areas could reduce the dilution of waste, particularly of pesticide residues, with effects on toxicity levels of streams and thus on wildlife. In the uplands increased winter rainfall could increase leaching and reduce the pH of soils, and thus increase risk of flood and erosion.

Effects on soils depend much on the future seasonal pattern and intensity of rainfall, about which we know very little at present. An increase in thundershowers might increase run-off, thus increasing flooding and soil wash. But it also might reduce percolation, thus decreasing the amount of water available for agriculture. Increased rainfall could increase the mineralisation of organic nitrates, allowing extra plant uptake, but it could also increase leaching downwards of soil nutrients. In any case, quite small changes in rainfall could require sensitive alterations to the drainage of soils.

We can only guess at the implications for weeds, diseases and pests. Warmer winters would extend the growing season of some weeds. For example, corn marigold which flourishes in warmer and damper weather, could become more of a problem. In the south of England scrubby, drought-resistant species (which already have a toe-hold in southern Britain) could increase their range (Grime & Callaghan, 1988).

Diseases which tend to break out more frequently in warm, damp conditions could also increase (such as rust *(Puccinia graminis)*, take-all *(Gaeumannomyces graminis)* and *Rynchosporium* in cereals, and *Rhizomania* in sugar beet).

Warmer winters could also increase the over-wintering of pests, and increase their range. This could affect populations of aphids, pollen beetles (which are a pest on oilseed rape) and slugs.

In summary, some of the benefits of warmer and drier growing seasons in the southern UK, and of warmer and wetter growing seasons in the northern UK, might well be offset by increased losses to weeds, diseases and pests.

POSSIBLE RESPONSES IN AGRICULTURE

While there are many uncertainties about how our climate will change in the future, there is one relative certainty about modern agriculture and today's farmers – it is that they have shown themselves capable in the recent past of adapting to a very wide range of conditions, both economic and environmental. The question, then, is not so much, 'can UK agriculture adapt to the greenhouse effect?' but 'what kind of adaptations would be most appropriate, and how can scientific research and government policy best help this process?'

Firstly, many of the smaller changes in temperature and rainfall might be accommodated by adjustments to the timing of farming operations. For example, were the number of rainfall days to increase between (say) mid-February and mid-April (during the period when wet days can restrict the drilling of spring crops and the application of herbicides and nitrogen), it might be possible to shift these operations forward by one or two weeks. Advantage could thus be taken of a longer and warmer growing season that would allow harvest of cereals in mid- to late June rather than July.

Indeed, earlier maturation might be necessary in the south and east of England (if increases in temperature coincided with little or no increase in summer rainfall), in order to avoid losses from mid-summer drought. However, earlier emergence of the crop could make it more prone to damage from late frosts (if these were to occur with undiminished frequency). A switch to some Mediterranean wheat varieties which are more resistant to late season frosts might be appropriate if they yielded well under longer daylengths.

Any change in the number of workdays involved in ploughing, drilling, spraying or fertilizing due to changes in climate would alter the costs of operations quite substantially. Once more, the number of raindays is important here – and again we know little at present about how these may alter.

Changes in the pattern of weather events may bring new uncertainties to the task of deciding when to undertake given operations. While potential yields may not be diminished (and may even be enhanced) the uncertainties about the cost of obtaining such yields may increase.

Secondly, in addition to changes in the timing of operations, there could occur a shift from spring to winter varieties of cereals, in order to avoid a higher risk of moisture shortage in the early summer, and to take advantage of a prolonged growing season in the autumn and an earlier onset of growth in the spring.

Thirdly, it may make sense to switch to varieties of crops that have a longer or more intense growing season requirement than our present ones. This would be particularly beneficial where varieties developed for growing at present near their northern limit are able to mature only at some loss of quantity or quality of grain.

Fourthly, we can expect farmers in the UK to consider switching to new crops which have higher thermal requirements and are at present perhaps grown in the south of Britain or in central and southern France. Sunflowers could become a more profitable crop, in addition to grain maize, and perhaps even soya (which is at present grown in northern Italy). Navy beans, also grown in northern Italy and for which the UK imports all its needs at present, might also be cultivable under a climate that could occur in southern England within the next 50 – 100 years.

Of course, any changes in the allocation of land to different crops would be influenced as much by changes in the potential for cropping elsewhere. If drier and warmer conditions obtained in Europe south of the English Channel, with reduced potential for the profitable farming of maize, sunflowers,soya, etc, then this might well increase the competitiveness of such crops for farmland in the UK.

In the uplands of Britain, it might not be too far-fetched to imagine that the increased productivity of improved grassland, together with decreased productivity further south in Europe, could act as a spur to improvement of rough grazings. Due to higher temperatures and the direct fertilizing effect of CO_2, trees (both conifers and broadleaved) can be expected to grow faster, and do better at higher altitudes than they do now (unless windspeeds increase) (Cannell *et al,* 1988). Together, these two enterprises could substantially increase demand for the uplands, increasing competition for land at present used for water catchment (which might itself need to be increased) and for wildlife and recreation.

Because these types of response will be interwoven in an incredibly complex way, it is probably not profitable to try to 'second-guess' them in detail. We need only recall, for example, that by 2030 (the estimated CO_2

doubling equivalent time for greenhouse gases) the World's population will also have nearly doubled from its present levels, and this could well alter the structure of demand and prices for food. These should not, however, be taken to imply that we should do nothing.

CONCLUSION

It is clear that we need to know much more about a number of aspects of likely changes in climate, particularly:

(i) what is likely to happen to the weather at the regional and local (rather than global) scale?;

(ii) how may rainfall alter, not simply on an average annual basis, but from season to season within the year? and

(iii) at what rate is the climate likely to change?

At the same time we need to know more about how quickly agriculture can adapt to the kinds of climate changes we may experience, and how we can assist in that adaptation. What, for example, is the potential for adopting crop varieties at present grown elsewhere? Or should we be thinking of developing new varieties now, since these may take about 10 years to develop and adopt? And what may be the cost of re-structuring agriculture (for example, what would be the cost of increasing irrigation to maintain in south-east England the kind of farming we see today, as against the cost of altering the type of farming there)?

These questions require several years more investigation before sufficiently detailed answers are likely to be available. It is probably unwise, therefore, to adopt a 'wait-and-see' attitude, particularly if there are disagreeable time lags in the climate system which imply that we are, even now, committed to some significant amount of climate change, and that the amount of change to which we will have to adapt will increase year by year the longer we delay an effort to reduce emissions of greenhouse gases. This suggests that, while continuing to pursue the scientific research to narrow the area of uncertainty about the greenhouse effect, we should also start thinking about the global agreements needed soon to reduce fossil fuel burning, improve efficiency in energy use and slow down the rate of deforestation.

Many of these policies of response would themselves have implications for agriculture in the future – such as policies to encourage afforestation in developed countries as a means of retrieving carbon from the atmosphere and storing it in trees, or encouraging the growing of crops that can be used in the production of alcohol as a substitute fuel for coal, oil and natural gas, or increasing the price of fuel to the consumer in order to reduce fuel consumption. (The latter could significantly increase the costs of fertilizers for agriculture.) The indications are that these policies will start to emerge within the next 4 or 5 years rather than 4 or 5 decades. Both the policies and the climate changes are likely to bring opportunities as well as costs for agriculture. It will be important to evaluate these opportunities and costs carefully, so that agriculture in the UK can respond in the most appropriate way.

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