Adaptation in agriculture: historic effects of heat waves and droughts on UK agriculture

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Extreme weather events are expected to increase in frequency and/or severity under climate change. Recent examples of these types of events, such as the heat wave in Europe in 2003, have caused considerable damage to crops and agriculture and substantial economic damage. If similar damage was incurred every time such an event occurred in the future, it would cause increasingly serious loss to social welfare and the economy as the frequency or intensity of these events increased. However, agriculture has a history of adapting to shocks, and in this paper we aim to determine whether there has been a systematic reduction in damage from historic extreme events over time in the agricultural sector in the UK. The impact of comparable droughts or heat waves over the past four decades is compared, and for many commodities there appears to have been a reduction in damage over time, to the point where recent events have had a minimal impact on production, indicating that the sector is relatively well adapted to the current climate. We discuss whether this type of adaptation can be sustained into the future under more rapid rates of change, or whether the 'low-hanging' fruits of adaptation have been picked.

Keywords: adaptation; agriculture; climate change; drought; heat wave

Introduction

As climate changes, events such as heat waves, floods, droughts, forest fires and hurricanes are expected to increase in frequency or severity or both (IPCC, 2007). Recent examples of this type of event, such as the heat wave in Europe in 2003, caused considerable damage to crops and agriculture, as well as significant loss of life and substantial economic damage (EEA, 2004; UNEP, 2004; Ciais *et al.*, 2005). Recent research highlights the damage that can be caused to regional and global markets by high seasonal temperatures. Battisti and Naylor (2009) calculated the difference between projected and historical seasonally averaged temperatures using output from 23 global climate models and showed that there is a greater than 90 per cent chance that growing season temperatures by the end of the 21st century will exceed even the most extreme seasonal temperatures experienced to date. If damage similar to the one caused by the 2003 heat wave occurred every time such an event would occur in the future, it would cause increasingly serious loss to social welfare and the economy as the frequency or intensity increased; although impacts in other parts of the world may lead to enhanced financial returns to UK producers through the global market.

Agriculture has, however, a history of adapting to various shocks in response to weather, policy, market or social conditions, often with radical impacts on production and well-being. In the UK, the projected changes in mean temperatures (Hulme *et al.*, 2002; Murphy *et al.*, 2009) may potentially have generally positive effects on agriculture at lower levels of projected change, with a longer growing season, possible CO_2 fertilization effects and the possibility to expand productive areas

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(Maracchi *et al.*, 2005; Easterling *et al.*, 2007; Moran *et al.*, 2009). Probably, the greatest threat to UK agriculture from climate change in the shorter term lies in the increased incidence of extreme weather events and emerging diseases. Extreme events such as droughts and heat waves have occurred in the past and changes have been made to cope with these. However, the concern with regard to climate change is the rate and magnitude of such events. The aim of this paper is to examine heat and drought impacts in the EU (and the UK in particular) over past decades of agricultural production, to observe the impact that these events have had, to identify whether the impacts have lessened over time, and draw out any observations or lessons that could be used to help inform future adaptation in the agricultural sector.

We compare similar type events over time in the UK to examine the extent to which adjustments were made which we infer to be adaptation in the sector. We examine whether this has resulted in greater resilience of the sector to that type of event, and whether there is scope for further learning. We hypothesize that as an event occurs more regularly, actors, in this case producers, learn from the previous events and take action to minimize future effects. If this was the case, then the impact of each successive drought would be less than the previous one.

Most evidence from agricultural economics, agronomy and meteorology suggests that increased frequency and intensity of extreme events from projected climate change (such as floods, droughts, heat waves and windstorms) are likely to lead to greater production losses than any increase in mean temperature over the coming decades (Hahn *et al.*, 2001; Porter and Semenov, 2005; Easterling *et al.*, 2007). Both short-duration events such as heat waves and floods, as well as longer-term events with sustained above normal temperatures have the potential to cause considerable damage to crops and yields depending on their occurrence in the growing season. Large-scale circulation changes, such as the El-Niño Southern Oscillation (ENSO), can have important impacts on production and therefore the gross domestic product (GDP), such as in Australia, for example, where GDP fell by 1.6 per cent (O'Meagher, 2005) as a result of an ENSO event. The 2003 heat wave in Europe resulted in a fall in corn yield in Italy by 36 per cent (Ciais *et al.*, 2005). The climatic conditions of 2003 are likely to be more common and are indicative of future summers (Schär *et al.*, 2004). Understanding the links between increased frequency of extreme events and ecosystem disturbances is very important; however, few models consider effects of climate variability as well as mean variables.

Using historical behaviour to observe how the agricultural sector has dealt with extreme events historically is one of the several methods that have been employed in an attempt to predict future behaviour, mostly in order to incorporate adaptation into modelling frameworks. As well as 'observed adaptation', which uses observed historical analogues to predict future behaviour, other methods have been identified as 'no adaptation', 'complete adaptation', 'arbitrary adaptation' and 'modelled (optimization) adaptation' (Tol *et al.*, 1998), and are described below.

Ignoring adaptation can lead to a serious overestimation of the damage of climate change. Many estimates of the impacts of climate change in agriculture (Rosenzweig and Parry, 1994; Parry *et al.*, 2004, 2005) do not represent adaptation, and have become known as the 'dumb farmer' approach. Agronomic research is used to estimate the impact of climate change parameters on particular crops in order to extrapolate these to wider environments and situations with an altered climate. These studies provide valuable insights; however, they do not incorporate any potential adaptations made by producers. The assumption of no adaptation occurs in many other fields, including health and danger from extreme events. Not only does this assumption lead to overestimations of damage, it also conveys the message that there are no actions available in the face of climate change and the only option is to mitigate emissions or suffer serious consequences.

Alternatively, other approaches (notably the hedonic or 'Ricardian' approach) (Mendelsohn *et al.*, 1994, 2000; Reilly *et al.*, 1996) use analogues from different climates affecting farming areas and use land values or other proxies to extrapolate the impact of a changed climate. Variation in capital values is taken as a reflection of the economic costs of climate change. While this approach is useful for providing first-order estimates of the economic impacts of production systems, it does not provide any information about specific adaptation options, their cost, effectiveness or any constraints to their implementation (Rosenzweig and Tubiello, 2007).

Other research has incorporated adaptation into the analysis at some arbitrary level – such as including 'no adaptation, some level of adaptation and full adaptation' as various options for comparing costs. This type of analysis can be very useful and may provide important information regarding the upper and lower bounds of costs. In the agricultural sector, Easterling *et al.* (1993) and Rosenzweig and Parry (1994) provide estimates of the potential of various arbitrary levels of adaptation to reduce damages of climate change, and arbitrary adaptation is assumed in many other sectoral studies, including air and water quality, coastal protection and air-conditioning.

Observed adaptation uses examples (analogues) from other situations as predictions of adaptation in the current situation. These analogues may be spatial or temporal. Spatial analogues use the experiences and actions in one location as examples or predictions of possible action in another similar location. Doing so can provide valuable insights but in terms of economics, the process and hence the costs of changing state are ignored (Tol *et al.*, 1998). Mendelsohn *et al.* (1994) use this method to estimate climate change impacts on US agriculture. Temporal analogues examine how adaptation has occurred historically, such as in this study.

Modelled adaptation uses the concept of a rational optimizing agent to either describe how decision makers do act, or how they should act. This type of study has been used mostly for decisions about coastal protection to date.

In summary, existing impact assessments make different assumptions about what adaptations to build into future damage trajectories. These assumptions amount to behavioural reactions which assume that agents either do nothing to avoid damages or they demonstrate more foresight, perhaps an unrealistic amount of foresight, into their anticipation of impacts and action to minimize them. The relevance of these strategies lies in the extent to which the assumptions overestimate or underestimate the costs of impacts, and by extension overestimate or underestimate the level of adaptation. As Hanemann (2000, p. 574) states, 'what is at stake in the debate on dumb vs. smart farmers is not so much the competence of farmers to run their business but rather the competence of analysts to model the farmers'. This study is an attempt to gain a more accurate picture of how farmers have actually adapted in the past, by using historical analogues to identify how agriculture in the UK may adapt to future extreme events, which may contribute to the understanding of how farmers react in response to climatic changes.

The paper is organized as follows. The next section describes the approach taken in this study, while the further section presents the findings. Finally, the last section provides a discussion of the issues raised and draws some conclusions based on the findings.

Methodology

This study in effect uses the historical analogue approach, although the focus is much more on observing what has occurred in the past rather than predicting adaptation into the future based on these results. We are interested in the effect of successive events. The hypothesis is that farmers learn from previous events, make adaptations, which mean that the impact of future events is minimized. The research approach involves first identifying the major droughts and heat waves that have occurred in the UK in the past four decades. Agricultural production data are then analysed to determine the impact on production in the years identified as being drought or heat wave years. The effect of these events on the value of production is also assessed.

We use documented sources to identify the main drought and heat wave years, to highlight the important characteristics of those events and to examine the impacts of those events on production.

Heat waves can have important impacts on many sectors of society, and projections regarding future temperature are considered more certain than those for future precipitation-related phenomena (e.g. Hulme *et al.*, 2002). The incidence of heat waves is projected to increase under climate change (Beniston, 2004; Luterbacher *et al.*, 2004; Schär *et al.*, 2004), which makes the impact and the response interesting to analyse. Because we are focusing on the agricultural sector, we will also include droughts, which may be more important for agricultural production.

Meteorologically however, droughts and heat waves have different characteristics (Chang and Wallace, 1987). While they may occur at the same time, intense heat waves have been also been observed during summers where soil moisture was abundant (and therefore not a drought). Major drought episodes tend to occur for months or even years, whereas heat waves typically last for a few days or a week. This has implications not only on the impacts of the episodes, but also on the options for adaptation. Notwithstanding this, a single heat wave lasting for a week or two can mimic drought conditions (Chang and Wallace, 1987). As a consequence, this research will include both droughts and heat waves in the analysis.

Agricultural production data for the UK are available only in an accessible form from the early 1970s; therefore, weather events since that time will also only be studied, although meteorological data are available for a much longer time scale. Several drought and/or heat wave events have been recorded since this time. Notable events occurred in 1975/1976, 1983/1984, 1990–1992, 1995, 2003 and 2006. Climatological classifications of the severity of these events (Philips and McGregor, 1998; Marsh *et al.*, 2007) suggest that these events are class 1 droughts (excluding 2006 which was not included in their analysis). This makes these years relatively comparable with each other. However, the effect of the event varies considerably by region in the UK. Spatial variations in drought severity, even within a region, can be significant (Marsh *et al.*, 2007). Despite this, at this stage, the analysis will focus on the UK as a whole rather than disaggregating it spatially.

Table 1 describes the main characteristics of the heat waves and droughts occurring in the UK since 1976. In some cases, a heat wave occurs during the drought, whereas in other cases (such as 2003) it was a shorter-term heat wave rather than an ongoing drought. Most of the other droughts are a result of several dry seasons.

No universally accepted classification scheme has been developed to define drought, which may be classified in terms of meteorological, hydrological, agricultural and socio economic conditions. Drought indices have been developed to reflect various definitions (Blenkinskop and Fowler, 2007). The droughts described above are all classified as 'major' droughts. Because these events are all relatively comparable in severity, they will be used as examples of extreme events to analyse the effect they have on production and to investigate whether there is any evidence for learning occurring in the agricultural sector.

The extremely high and sustained temperatures of the 2003 European heat wave led to several studies re-examining the relationship between rising mean temperatures and rising extremes of temperature and the implications of this for the frequency of future heat waves. Comparatively small shifts in the mean climate can imply pronounced changes at the tails of the statistical distribution of weather events (e.g. Wigley, 1989) and hence in the frequency of extremes. Following the 2003 European heat wave, Schär *et al.* (2004) showed that the tail of the probability distribution of European summer temperatures might be considerably wider than previously thought. The mean summer temperature in Europe in 2003 exceeded the 1961–1990 mean by around 3°C (Luterbacher *et al.*, 2004), which Schär *et al.* (2004) suggested corresponded to an excess of up to 5 standard deviations. Schär *et al.* also found evidence for a shift in the distribution of monthly temperature

Table 1 | **Characteristics of major drought and heat wave years in the UK**

Year	Duration	Characteristics
1976	May 1975–August 1976	Major drought. Lowest 16-month rainfall in England and Wales series (from 1766). Extreme in summer 1976. Benchmark drought across much of England and Wales. Lowest flows on record for majority of British rivers. Severe impact on surface water and groundwater resources
1983/1984	June 1983–October 1984	Borderline as a severe drought, with considerable regional variation
1990–1992	Spring 1990–Summer 1992	Major drought. Widespread and protracted rainfall deficiencies – reflected in exceptionally low groundwater levels. Intense phase in the summer of 1990 in southern and eastern England. Exceptionally low winter flows in 1991/1992
1995–1997	Spring 1995–Summer 1997	Major drought. Third-lowest 18-month rainfall total for England and Wales. Long-duration drought with intense episodes and hot summer (heat wave) of 1995. Initial surface water stress, then very depressed groundwater levels and much diminished lowland stream network
2003	June–August 2003	Heat wave across UK and Europe. Extreme temperatures repeatedly recorded in July and August. The all-time maximum temperature record was broken in the UK at 38.1°C. Large parts of Europe and UK affected by drought
2004–2006	2004–Winter 2006	Severe in the English lowlands and south-east. June and July 2006 were second driest in 23 years

Source: Adapted from Marsh *et al.* (2007)

anomalies, implying a change in the underlying mean climate state.

Estimating return periods of events such as this is a precarious statistical exercise and depends substantially upon what one assumes the baseline conditions to be. The length of reliable temperature observations is also a constraint on deriving robust estimates. For example, if one assumed the period 1961–1990 represents the baseline climate for central Europe, then Luterbacher *et al.* (2004) showed that the return period of the 2003 summer is less than 100 years. On the other hand, if one uses mid-18th century summer conditions as the baseline then the return period of 2003 may be as high as 5000 years.

However, if one interprets the 2003 summer heat wave in statistical terms, there is convincing model-based evidence that the frequency of heat wave events similar to 2003 will increase in the future. Stott *et al.* (2004), using projections with the HadCM3 model, showed that the probability of European mean summer temperatures exceeding those of 2003 increases rapidly under the SRES A2 emissions scenario. They estimated that by the 2040s decade more than half of the summers would be warmer than 2003. They also stated that, for their model and the A2 scenario, by the end of this century, 2003 would be classed as an anomalously 'cold' summer relative to the climate then prevailing.

The implications of these findings relate to heat waves rather than droughts specifically, although projections for precipitation and temperature in the future suggest drier summers with less rainfall and higher temperatures (Hulme *et al.*, 2002). Marsh *et al.* (2007) show a clear increase in the severity of summer droughts in the 20th century, relative to the 19th century, driven mostly by rising temperatures. However, in relation to hydrological resources, winter rainfall is of primary importance and the authors find no clear increase in rainfall deficiency (drought episodes) over time. However, they do make the point that with temperatures, water demand and the expectations of stakeholders continuing to rise, any repetition of rainfall patterns that characterized several 19th-century droughts would represent a considerable challenge to the water industry in the UK.

This study uses national annual production data for each commodity, sourced from Defra[1] and the FAO.[2] While using national-level data undoubtedly hides regional variation and may in some cases present a misleading picture of impacts, on another level it does represent the ultimate picture of the performance of the sector for that year. Other studies assessing the impacts of extreme events (e.g. Subak, 1997; Hunt *et al.*, 2006) on agriculture have estimated the costs using gross margins. While the gross-margin approach provides a useful insight into farm-level costs, it allows other factors to enter into the calculation, including input costs and subsidies. Using final production levels provides a picture of what is happening to the focus of interest in the case, that is, production, and not specifically the costs to the producers.

We investigate the impacts of droughts and heat waves on five crop commodities (potatoes, sugarbeet, oilseed rape, wheat and barley), and four livestock categories (beef cattle, sheep, pigs and poultry). Dairy production was not included as it was felt this was too influenced by policy for production to provide a reliable picture of weather impacts. Data are available for most commodities from 1970 to 2007. Production in the 'event years' is compared to production in the five-year moving average (MA) to account for trends over time. Data from event years are excluded from the MA calculation.

Results

Production during drought and heat wave years

This section examines production during the drought or heat wave years considered, in order to determine whether there is any consistent pattern which would indicate that adaptation to this type of weather event has occurred over time.

Figure 1 illustrates the percentage deviation from the five-year MA (excluding the event years) for the years where class 1 droughts or heat waves were known to occur. These figures tell a mixed story. For potatoes, oilseed rape and wheat to a lesser extent, there does appear to be a pattern of decreasing deviation from the mean for successive events. This is in line with our hypothesis that as events occur more regularly, actions are taken to minimize the damage or losses that occur, so that over time the events do not cause the same degree of damage. By 2003 and 2006, production was hardly affected for these three crops.

However, sugarbeet and barley do not show the same pattern. Unfortunately, the production data for the 1975/1976 drought were not available for sugarbeet, but other studies (e.g. Subak, 1997) show that the yield was very negatively affected during that event. If that was the case, then it may be that sugarbeet production would show a similar trend.

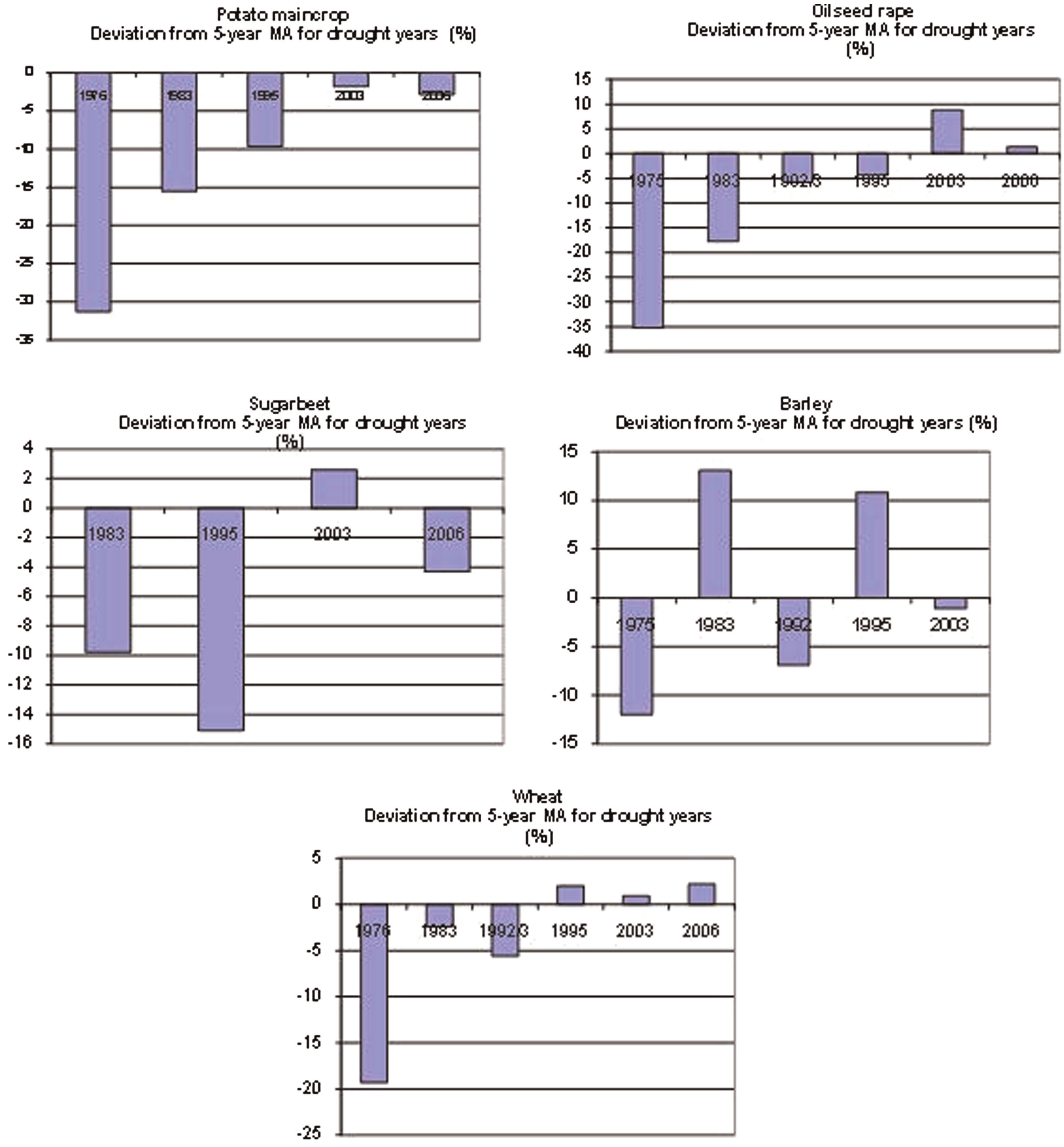

Figure 1 | Deviation from five-year MA for drought years for selected arable crops

However, yield was affected more heavily in 1995 than in 1983, and more in 2006 than in 2003, which does not indicate any systematic minimization of effect. Barley does not show any strong pattern, with the two droughts of 1983 and 1995 resulting in increases above the mean, while 1975, 1992 and 2003 showed decreases. On the positive side however, the deviation below the average did decrease over the three drought years that occurred.

Livestock information is shown in Figure 2. The effect of a drought or heat wave may often not be felt in the year it occurs because farmers may sell more stock, resulting in increased production. The effect on production may be observed in subsequent years as farmers rebuild their herds and production may decrease. Recent examples of this occurred on a large scale in Australia, where drought conditions caused producers to reduce animal numbers from between 4 and 10 per cent (Hopper and Crooks, 2008). Recovery from the drought conditions has resulted in fewer numbers slaughtered, as producers build up their herds again. Because of this feature of

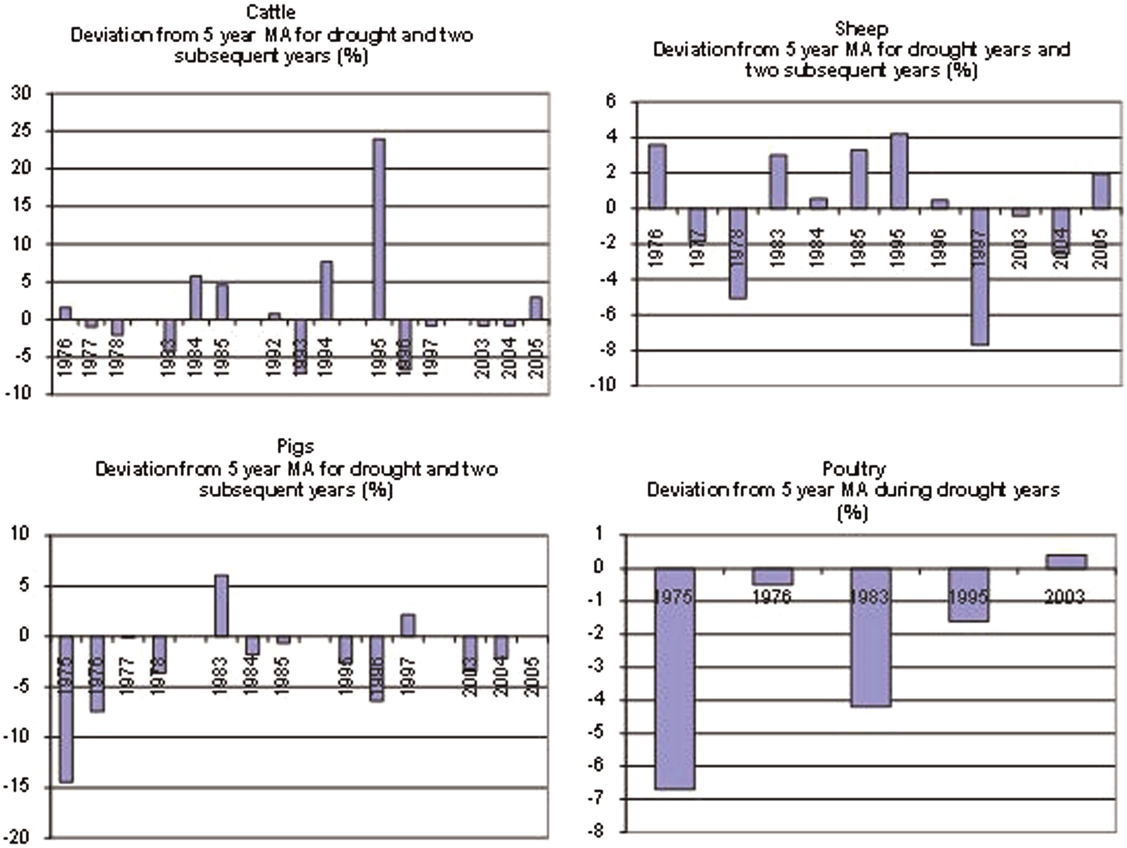

Figure 2 | Deviation from five-year MA for drought years for selected livestock (per cent)

livestock production, the two years following the climate event are also shown in Figure 2 (with the exception of poultry as it operates in quite different production systems that are much shorter and the lagged effect does not occur).

In the livestock sector, it is more difficult to differentiate the causes of differences in production than in the arable sector, because other factors will impact on total production. In arable crops, the yield is most dependent on climate, whereas changes in policy or markets will affect the total production rather than yield because of changes in the area planted. In the case of livestock, yield (or carcass weight) is less readily available and does not show large variation between years, whereas animal numbers and production are more indicative of change – but this change could also be due to policy or other non-climatic changes.

In the case of sheep, meat production in the drought years increased for all years apart from 2003. As discussed, this may be due to farmers reducing their stock numbers because of less feed and rising feed costs. Following the 1975/1976 drought, production fell in the following year, 1977, and even further in 1978. This may be due to farmers rebuilding their herds, and not selling stock, and therefore an effect of the drought. Production also increased in 1983, and although it was still above the mean for the next two years, it was below the 1983 level. A similar pattern occurs in 1995, although two years later, in 1997, production fell substantially, which is not likely to be wholly attributed to the drought. In 2003, production fell slightly. In terms of evidence of the impacts reducing over time, the sheep sector does not appear to show this.

Cattle demonstrate a similar pattern, with production slightly above average in 1976, then falling below average in 1977 and 1978. This is demonstrated strongly again in 1995 (there is a slight effect in 1992 but in 1983 production falls, which does not uphold the theory) when production increases significantly but falls again in 1996 and 1997. In 2003, production falls. There does not appear to be any pattern in terms of reducing the impact of successive events.

In the pig sector, production fell dramatically in 1975 and 1976. In the 1983 event, production increased in that year but fell in 1984 and 1985. In 1995 and 2003, production fell in that year as well as the following year. There may be some evidence of adaptation in this sector as the subsequent drought/heat wave years have had a considerably smaller effect than the effect of the 1975/1976 event. Poultry demonstrate a much tidier picture of adaptation to these types of events. The deviation in production from the five-year average in 1975 was almost 7 per cent, by 1983 it was just over 4 per cent and by 1995 it was under 2 per cent, and in 2003 production increased.

The method used here is not able to say with any certainty that the changes in production or yield are due to climate change or even weather variables. The aim of this research is not to determine the effect of weather variables on yield, but rather to examine the impact on production during drought years. As the series of drought years is very short (six events), it is not possible to carry out a regression on these years. So we cannot say with any statistical certainty that the impact during those particular years is due to drought or heat wave, but knowing that a drought or heat wave occurred in that year, we are interested in the ultimate impact on production.

Discussion

This section provides a discussion of the implications of these findings in light of the ability of UK agriculture to adapt to future extreme events.

What occurred after the events?

Possibly the single biggest action which has led to reduced impact from droughts and heat waves over time, certainly in the arable sector, is irrigation. Irrigation flow in the UK has increased from 55,210cumecs in 1982 to 164,070 in 1995 and 92,883 in 2005[3] (Weatherhead, 2007). Some crops are much more responsive to irrigation than others, such as potatoes, which can improve both yield and quality substantially if they receive water at specific times in their growing cycle. Large investments were made in irrigation equipment for potatoes following the drought years of 1975 and 1976. In 1975, only around 12 per cent of the potato crop was irrigated in a dry year, but by 1978 this figure had risen to 21 per cent. From the mid-1970s onwards, there has been a steady increase in the percentage area of the crop irrigated, reaching 46 per cent in 1995 and 60 per cent in 2001 (Cannell *et al.*, 2003). After the 1995 drought, there was a general increase in investment in irrigation on vegetable units, particularly lettuce (Orson, 1996). However, in long-term droughts, or droughts that occur over consecutive seasons, irrigation may not be an option or may at the least be restricted, if water storage levels are low. Prioritization between crops may become an important consideration. In 1995, few growers had sufficient water and application capacity to allow them to adequately irrigate their crops. However, some crops, such as sugarbeet, have a wider growth-stage window within which water can be used effectively, and so these types of crops can be irrigated at times when other crops do not have peak demands. Nonetheless, water storage has increased in the UK over the past few decades, nearly doubling between 1984 and 1995 (Orson, 1996). This increases the ability of producers with access to irrigation infrastructure to irrigate.

The response of cereals to irrigation has however been uneconomical in the UK and the adaptive responses have been related more to the time of sowing and harvesting, as well as the introduction of rapidly maturing cultivars (Orson, 1996).

Other adaptive measures documented during or after these events include the planting of increased areas to allow for a lower yield. This occurred with potatoes in the 1975/1976 event. Whether this is a long-term solution is uncertain as the opportunity cost of the land must be considered. Changing growing schedules to avoid late summer maturation and shifting the production types to different parts of the country have also occurred.

Although detailed studies covering the responses of the agricultural sector in the UK to these events are patchy, they do provide a picture of some of the actions that were taken, and in many cases they have improved the resilience of the sector to future similar events.

Is agriculture adapted to the current climate?

There is evidence across most of the commodities studied here that the effect of subsequent events on production declines over time. This would indicate that adaptation to these events has occurred. The 1975/1976 drought caused serious losses in yield which have not been repeated since. This is hypothesized to be due to several factors, including institutional learning, improved technology and increased awareness and practical strategies among producers to cope with drought.

However, the effect does vary considerably across commodities. This variation is likely to be due to a number of reasons, including the sensitivity of the crop or animal to water stress and heat, the responsiveness of the crop to irrigation and the relative value of the crop or livestock in relation to the cost of adaptive measures. Some commodities may be at the upper bound of being able to adapt, while others may be able to tolerate a greater degree of change and still be able to cope. In terms of representing adaptation in impact assessments, most models of impacts of climate change have a relatively high level of aggregation and agriculture is likely to be included as a whole rather than disaggregated by commodity. An average adaptation rate for agriculture as a sector is of course necessary in large-scale models; however, as with any aggregation, the individual impacts become lost.

The analysis of production during extreme events is at the national level in the UK. This introduces a certain level of imprecision because the regional effects will vary considerably. The weather effects will be different in different locations and hence in some regions the impact of a drought will be much more severe than in others. Additionally, although the events were all of comparable magnitude, their timing and duration did vary and hence the effect on the growing cycle of the plants or livestock will vary as well, making direct comparison of events difficult.

Perhaps the most important consideration is that there is no guarantee that the historical rate of adaptation to climate change can be maintained into the future. Some of the changes made during these last few decades were relatively simple to enact and occurred at a time when other pressures may not have been acting on agriculture. An example of this is irrigation, which is a relatively straightforward adaptation to make. Once the irrigation is installed, further adaptation options may not be as accessible (the low-hanging fruit analogy). Additionally, due to increasing pressure on water resources, and reduction in rainfall in some areas, installing new irrigation or drawing more water out may no longer be possible or economically feasible. Furthermore, if future droughts or heat waves increase in their intensity, or occur over longer periods of time, or in succession, water supplies may be restricted and irrigation may not be feasible.

Is efficient adaptation likely?

While the results presented here, and the other approaches to representing adaptation in models discussed earlier, make different assumptions about adaptation and tackle it in varying ways, they share some common weaknesses, which must be overcome if adaptation is to be represented more realistically. The first of these is that many of the costs associated with adaptation are not included in analysis, that is, it is assumed that adaptation will be cost free. While this may be true for some routine changes that can be absorbed in the daily management of a system, many adaptations will incur significant costs. Adaptations may be complex and interact with other practices and policies, and most of the existing studies make simplistic assumptions about adaptation (as indeed this study also does). Studies tend not to distinguish between anticipatory and reactive adaptation, which however may have important implications for the costs and the outcomes. In addition, adaptation is often considered in an equilibrium context, whereas adaptation costs tend to be a transitory phenomenon (i.e. adaptation as process rather than as outcome).

The decision (or the ability) to irrigate is perhaps a key for adaptation in UK agriculture, for some crops particularly. Earlier exchanges concerning the modelling of irrigation in the hedonic or Ricardian approach (Hanemann, 2000; Schlenker *et al.*, 2005; Kurukulasuriya and Mendelsohn, 2006) highlighted the importance of the assumptions about irrigation and the consequent implications for welfare. Considering irrigated land separately from non-irrigated land in the hedonic approach was shown to be important (Schlenker *et al.*, 2005), but so was the process of moving from non-irrigation to irrigation (i.e. treating irrigation as endogenous rather than exogenous) (Kurukulasuriya and Mendelsohn, 2006). The process of adaptation and the decisions that influence it are perhaps more important than the comparison of impacts under climate change with no impacts. As Hanemann (2000) states, the issues lying at the heart of climate change concern dynamics and disequilibrium.

This study has not attempted to calculate the costs or the benefits of adaptation in the agricultural sector specifically, preferring at this stage to look at the overall effect of extreme events on production and producer prices. Given the importance of making accurate decisions about adaptation, the next step would be to attempt to assess the costs and benefits of adaptation actions. This is a research and policy area that is gaining considerable importance; however, there are several factors that make valuation of adaptation very complex (Agrawala and Fankhauser, 2008; Watkiss *et al.*, 2009).

Adaptive capacity in UK agriculture

Adaptive capacity is a vector of resources and assets that represent the asset base from which adaptation actions and investments can be made. This capacity may be latent and be important only when sectors or systems are exposed to the actual or expected climate stimuli. Vulnerability to climate change is therefore made up of a number of components including exposure to impacts, sensitivity and the capacity to adapt. Adaptive capacity has diverse elements encompassing the capacity to modify exposure to risks associated with climate change, absorb and recover from losses stemming from climate impacts, and exploit new opportunities that arise in the process of adaptation.

While the picture presented in this paper may indicate that agriculture in the UK is relatively well adapted to current climate variability, there are controversies on the ability of agriculture, and societies in general, to adapt to climate change. It is frequently assumed that the capacity of societies to adapt to climate risks is based on their level of economic development: the more economically 'developed' a society, the greater the access to technology and resources to invest in adaptation (see discussion in Smit and Pilifosova, 2001; Yohe and Tol, 2002; Adger and Vincent, 2005; Brooks *et al.*, 2005). There is debate on what constitutes the capacity of a sector, region or country to adapt to climate change – are the elements of adaptive capacity generic and related to levels of economic development, or are they specific to climate risks faced? Future changes in climate may test the capacity of UK agriculture to adapt. While gradual temperature change is likely to have mostly positive effects in northern latitudes, extreme events such as those discussed in this paper will pose the greatest threat. There are several potential barriers to adaptation, which may undermine the adaptive capacity of the sector. Some of these may be structural or even physical, such as being locked in to a certain production type because of the physical characteristics of the land and perhaps being unable to sell the land. Other barriers may lie in social capital and the behavioural characteristics of producers and their attitudes to risk, as well as their relationship with government agencies. Hall and Pretty (2008) argue that a decline in public extension services in agriculture and a breakdown in relationship with government agencies have hindered transitions to more sustainable land management in the UK. Attempts by intervening agencies to persuade farmers to change behaviour were often perceived by those communities as patronizing as they devalued local knowledge and experience. Moran *et al.* (2009) highlight the risks of repetition of such perceptions in the context of adaptation to climate change, where some farmers emphasize that they have historically adapted to changing conditions and advice on adapting to climate change may be perceived as being unnecessary and simply adding to the restrictions on their business.

Furthermore, the focus of this study has been on drought and heat waves. Other manifestations of climate change including flooding, changes in wind speed and the possible increase in pests and diseases are all likely to present significant challenges to the agricultural sector in addition to and in some cases exacerbating the effects of drought and heat waves, and adaptation options may be limited. Conversely, changes in growing season and milder winters may create opportunities for production.

Sustainability and adaptation

So far, this paper has assumed that adaptation to climate change in the agricultural sector involves maintaining or increasing historical levels of production. However, in a changing climate preserving the *status quo* may not always be appropriate. Climate change may mean that certain types of production are no longer suitable in a given area, and 'pushing' the system in terms of increased irrigation or inputs of fertilizer or pesticides may have wider negative environmental consequences on biodiversity, groundwater or greenhouse gas emissions (see e.g. Firbank *et al.*, 2008; Pretty, 2008; Smith *et al.*, 2008). On the other hand, moving production into new areas that become more suitable under changing climatic conditions can also have implications for biodiversity, carbon storage and water quality (Firbank *et al.*, 2008; Lal, 2008; Moran *et al.*, 2009). Trade-offs and synergies between the sometimes diverse aims of both climate change mitigation and adaptation, as well as wider environmental and social considerations, need to be identified and managed.

Conclusion

UK agriculture has, as one would expect, the technological and financial capacity to adapt to challenges posed by climate change. It has shown as a sector that it can exploit opportunities presented by changing circumstances, it is generally supported by government and society and is able to take advantage of new research and technology as they become available. The research in this paper is based on the idea of learning from the past; however, some adaptations to climate change will be more effective (and cost-effective) if they are employed in anticipation of events, rather than in reaction to them. However, producers have many competing demands on their resources and are unlikely to spend time and money on actions that have uncertain future benefits.

The choices farmers make, and the factors that influence those choices, will determine how UK agriculture actually does adapt to future changes in climate. How long producers take to perceive changes in climate and to decide they are significant and permanent enough to respond to, how they perceive the relative importance of climate change together with other pressures they face and whether they are able to make the changes they would like to or are locked into current practices through various forms of barriers will all determine the future state of agriculture in the UK. Or as stated by Hanemann (2000), what is optimal depends on a number of considerations: what you think the choice is about; what you see as alternative courses of action; what your objectives are; what you perceive to be the link between the alternatives and your objectives; and what your constraints are. And these are not readily knowable, and will vary between individuals and circumstances. Thus, despite the relatively high adaptive capacity of UK agriculture, the way in which agriculture will respond to climate change and the success of actions in the future cannot be taken for granted. This research has shown, however, that in the past farmers have made adjustments so that their enterprises are less affected by droughts and heat waves.

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Notes

1. https://statistics.defra.gov.uk/esg/publications/auk/2007/
2. http://www.fao.org/corp/statistics/en/
3. The decline in irrigated area since 1995 may be a data issue as data up to 1995 included England and Wales, but after 1995 is for England only.

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