Agriculture and Forestry Climate change report card technical paper

3. Arable Crops

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Summary

- The effects of change in climate on crop production should be considered in relation to very large changes of 2- to 10-fold that have occurred over the past 70 years in crop-areas, fertiliser, pesticide, tillage and yield.
- The combined effects of change in temperature and CO_2 concentration on the main cereal crops will (contrary to some simplistic predictions) be very much smaller than the changes referred to above.
- Increasing incidence of dryness in the south of the UK will likely cause the most systematic and important reductions of yield. Irrigation would have to compete with other industrial and domestic demands for water. Effects of high rainfall in the north acting through saturation of soil and waterlogging are potentially important but have not been adequately researched.
- Evidence from the very wet autumn of 2012 and the highly favourable year of 2014 suggest single-year impacts on yield of less than a factor of 1.5 (i.e. between 0.7 and 1.5 of the ten-year mean yield).
- Pests (weeds, invertebrate pests and diseases) will inevitably be affected by changes in temperature and water, but the interactions between pests and crops are highly complex, non-linear and hard to predict. Given the range of pest species and their known ability to evolve, pests in general are likely to adapt quickly to climate change.
- The essential and beneficial biota of the soil and above-ground habitats are being reduced by continued intensification and inappropriate soil management. Remedial action is needed in advance of any further effects of climate.
- There are many ways that agriculture can mitigate and adapt to climatic change. It can
  - pay more attention to cropping systems than single crop species such as wheat;
  - increase the diversity of crop species, varieties and economic products;
  - stabilise crop production through undersowings, mixtures and intercrops;
  - implement long term soil management to increase soil carbon and reduce compaction;
  - enhance positive microbial associations in crop production, namely nitrogen fixing in legume crops and forages and mycorrhizal associations;
  - breed crop varieties for coping with multiple stresses rather than just maximising yield under ideal conditions.
- Food security is already a matter for concern in the UK. The country depends on imports of food, feed and fertiliser for its sustenance, while a large part of its produce is grown for industrial feedstock or exported. The gaining of food security will need a wholesale redirection of effort to grow more crops for local consumption on local resources.

BACKGROUND TRENDS AND DYNAMICS IN ARABLE CROPS

Main trends and periods 1940-2010

Effects of current and future variable weather should be seen in the context of very large shifts in arable and arable-grass agriculture over the previous 70 years. There were three main phases, each of about 20 years: (1) post-war reconstruction and the beginnings of intensification, (2) the main phase of intensification and (3) levelling and adjustment. Sources of information are listed in Appendix A.

1.1 Consolidation and reconstruction (late 1940s to late 1960s)

The balance in area sown with the main crops began to change in the late 1940s, but there was slow progress towards intensification as it is understood now and inputs and yields did not begin their rapid rise until the next phase.

In the early 1950s, oat was still the most widely grown cereal, the proportions of oat:barley:wheat being 40:30:30, but then oat decreased by 5 times as barley increased. By the end of the period the proportions were oat:barley:wheat = 8:61:31. Yield averaged over the UK in the early 1950s was 2.7 t ha^{-1} for wheat, slightly less for the other cereals. Increase was small (e.g. about 1.2 times in the first decade but over the two decades was around 1.6 times. The contribution of increased inputs to this early rise in yield are uncertain due to scarcity of census records. Nitrogen inputs began a period of major increase while phosphate remained stable, but comprehensive pesticide surveys did not begin on arable crops until 1974. Nevertheless, various sources indicate small inputs of pesticide compared to later years.

1.2 Intensification: 1970s to mid-1990s

Yields of the main crops began to rise more steeply in absolute terms during the 1970s in response to increasing inputs, particularly of nitrogen and new crop genotypes. This period constituted the main phase of intensification in 20thC UK. The first pesticide survey in 1974 was a baseline for estimates of increase over the next 20 years.

Increase in yield occurred by shifts in area to higher yielding wheat and through yield per unit area. Wheat increased almost 2 times in area at the expense of barley. Increases in winter barley and winter oilseed rape completed the transition to mainly winter cropping in the UK as a whole. From the mid-70s to the mid-90s, yield increased by a 2.7%, 3.7% and 2.9% per year for barley, wheat, and oat, respectively (FAOSTAT, 2015). By the early 1990s, yield of wheat was around 7.2 t ha^{-1} in the UK as a whole, a rise of 2.6 times from the early 1950s. Other crops such as potato and winter oilseed rape also showed consistent rises in yield during this period. Nitrogen usage on all crops and grass increased by around 2 times up to the mid-1980s, driving the rise in yield, then began to decline from the early 1990s (see next phase). Despite some major fluctuations, phosphate application began a long term decline as agriculture realised there were stores of phosphate in the soil that had accumulated during previous periods of over-application. Use of pesticides increased throughout the period for most crops. Given the many different types of pesticide and the methods used to characterise them, no attempt is made here to quantify increase by a simple raising factor. However, increase occurred variously through the number of different active ingredients, the number of times fields were treated in a year and the specificity of the target, e.g. rise in broad spectrum herbicides that killed most weed species (Marshall et al. 2003).

1.3 Levelling of yield and decline of some inputs (1995-2015)

The phase of intensification, typified by broadly rising inputs and yield had come to an end, except for pesticide inputs which continued to increase for the major high-input crops.

Potato received the highest applications of pesticide and phosphate while winter oilseed rape received the highest nitrogen. Winter wheat was the most intensely managed crop in total.

Areas of the crops showed little change compared to previous periods, except for fluctuations due to set aside and oilseed rape, the former causing a levelling of total grain output. The previous rise of yield per unit area slowed and then levelled for the major cereal grain crops in the early 1990s.The only crop to show a consistent, though small, increase was oilseed rape, and part of that especially in the north was due to the shift from spring-sown to higher yielding winter varieties. Nitrogen application diverged for tillage and grass crops – application to all tillage crops levelled at around 150 kg ka^{-1} while that to grass declined by almost 2 times, leading to an overall fall in N applications to UK agriculture. Phosphate application continued to decline (see previous phase), proportionately more to grass crops, but overall by 2 times over the two decades from the mid-1990s. The decline of phosphate application that began in phase 2 is the single most consistent trend in UK cropping over the past 70 years. The main input that continued increasing during this phase was pesticide. The area treated with all active ingredients increased for cereals, oilseed, potato and most other crops.

Over the period 1961-2013 the percentage annual growth rate in terms of area harvested, production, and unit yield was -1.9%, -0.7%, and +1.1% for barley, +1.7%, +3.4%, and +1.6% for wheat, and -2.9%, -1.5%, and +1.3% for oat (FAOSTAT, 2015). The production system therefore had come to rely heavily on wheat.

1.4 Short term dynamics and effects of extreme-weather years during intensification

The trajectories described above made it difficult to assess effects of unusual weather on inputs, yield and crop-areas, particularly during the intensification of phase 2. Further 'noise' has been generated by superposed shifts in a wide range of ancillary variables over a timescale of 5-10 years. For example, in the 1990s, the use of glyphosate as a broad spectrum herbicide increased from very little to being among the top most widely applied herbicides. Similarly land set aside increased from zero to around 10% in the 1990s and then decline substantially. Various directives on the application of nitrogen caused fluctuation in inputs in the mid-1990s.

At the end of period 2, though it was not realised as such at that time, Squire & Unsworth (1988) could cite little empirical evidence for the effects on yield of, say, previous hot summers or wet autumns and winters, simply because little attention had been paid to such fluctuations. However, one example towards the middle of phase 2 (intensification) was offered by the increasingly hot dry summers of 1975 and 1976 that gave experimental evidence of high temperature, coupled with low rainfall, shortening phenological phases in determinate cereals, and thereby reducing grain yield (Gallagher, Biscoe & Hunter, 1976). National yield of wheat fell from 5.0 t ha^{-1} in 1974 to 3.9 t ha^{-1} in 1976 (a factor of 0.78). However, fluctuations of this size - and there were several in the 1970s and 1980s - were little more than blips in the steeply increasing upward trajectory that did not begin to level off until the early 1990s.

The levelling of yield in phase 3 possibly offers better material for examining the effect of unusual weather (e.g. Palutikof, Subak and Agnew (1997) Economic impacts of the hot summer and unusually warm year of 1995. Defra, London. ISBN 0-902170-05-8

Notably, the cause of the substantially depressed yield due to wet weather in 2012 has not been apportioned between physiological suppression and restricted operations. However, a degree of resilience was evident by the shifts in areas among the various crops (including evidence of a reliance on oat), the rise in yield the next year and the much greater rise in 2014 due to favourable weather.

1.5 Summary and Conclusions on background trends

Characteristics of the agricultural system have changed substantially during the last 70 years. The main trajectory of rising yield and inputs has stalled, though pesticide inputs continue to rise, causing yield per unit pesticide to decrease.

Most of the trends occurred before the run of high-temperature years since 2000 and were caused by factors not primarily related to climate. Changes of this type will undoubtedly continue to occur but are difficult to predict. Uncertainty in the future trajectories of yield and inputs limits our ability to predict change solely due to climate.

EFFECTS OF CLIMATIC FACTORS ON CROPS

2.1 Temperature

Climate projections suggest there will be a general increase in mean temperature in the UK within a range in which developmental time is inversely related to temperature. Accordingly, the increase in temperature would speed the passage of plants through developmental stages. The resulting effect on growth and yield would depend on whether the plants were determinate or indeterminate. Increasing mean temperatures will shorten the growth period of determinate crops, including cereals such as wheat and barley (Mitchell et al. 1993; Wheeler et al. 1996; Harrison et al. 2000; Ghaffari et al. 2002; Cho et al. 2012) and legumes such as faba bean (Peiris et al. 1996), and, consequently, reduce their yield potential. However, this effect would be offset by increasing CO_2 concentration (see below). Yield of the main cereals would not therefore be strongly affected.

In contrast, an increase in temperature will affect indeterminate crops such as some forms of potato, sugar beet and vine peas by increasing the rate of expansion of the canopy and root system, and hence lengthening the period in the year when the canopy is potentially able to take in resources, provided there are no other factors preventing earlier planting or later harvest (Davies et al. 1997; Richter et al. 2001, 2006; Jaggard et al. 2007; Evans et al. 2010; Gregory & Marshall 2012). Yield potential would therefore increase for indeterminate crops, especially when combined with increasing CO_2 concentration, although the magnitude of the increase in yield will depend on the crop and on other limitations (Wurr et al. 2000; Wolf 2002; Wolf & van Oijen 2002; Pidgeon et al. 2004; Richter et al. 2006; Evans et al. 2010).

There might be some changes in the geographical distribution of crops. Relative yields of indeterminate crops are likely to increase most in northern England and Scotland. There might be a northward shift in the cultivation of wheat (Cho et al. 2012). Breeding for longer grain filling durations could increase or stabilise yields in regions where sufficient water is available (Richter & Semenov 2005). It is predicted that there might be a westward shift in the cultivation of sugar beet (Davies et al. 1998). Similarly, increased mean temperature and rainfall in northern England could increase its suitability for the production of forage maize (Davies et al. 1996).

2.2 Rainfall

There is strong regional variation in rainfall across the UK, and this is likely to increase. In addition, extreme events could have large effects (see below). The availability of water is considered to be the main threat to crop production in the UK arising from climate change and is likely to be the greatest cause of variability in crop yields between years. However, no major shift away from current crops towards exotic crops is expected in the near future (Gibbons & Ramsden 2008), but there may be regional shifts in currently minor crops such as grape vine and fruit. There are significant interactions between temperature and precipitation affecting soil water availability that would impinge on the seasonality of crop growth and development. These effects have been incorporated into most models predicting the effects of climate variables on crop yields. However, the potential interactions between mineral nutrition, declining soil conditions (e.g. soil organic matter and increasing soil strength), root system development and water availability to crops have been rarely considered.

The yields of unirrigated wheat, barley, forage maize, oilseed rape and sugar beet are already limited by water availability in some regions of the UK (Davies et al. 1996; Jaggard et al. 1998; Pidgeon et al. 2004; Evans et al. 2010; White et al. 2015). Yield losses in these regions are likely to become greater and more frequent through climate change. It is anticipated that water scarcity will reduce yields of rainfed cereals, oilseed rape and sugar beet in the south of England, but increased rainfall will increase yield in northern England and Scotland that are presently limited by water (Jaggard et al. 1998; Butterworth et al. 2010; Evans et al. 2010; Stratonovitch et al. 2012). Similarly yields of rainfed beans are likely to increase in regions with increased rainfall (Peiris et al. 1996). The geographical yield differential between UK regions might, therefore, widen.

Implications for irrigation

Currently, most field irrigation water is applied to horticultural and potato crops. To maintain yield in the future, they would require more irrigation in southern England to compensate for the reduction in rainfall, and possibly less irrigation in northern England and Scotland. If irrigation is not fully available to meet the demand, there are projections that land used for cultivation of potato in England and Wales will decline between 74% and 95% of the present value, depending on the projected climate scenario (Daccache et al, 2012). The use of additional irrigation water is a limited possibility in most of the cultivated areas because they are in catchments where water is already used at the maximum level. Population growth, industry and other agricultural business will compete for the amount of water available.

The adoption of irrigation could also be used to increase the production of other crops including cereals, oilseed rape and sugar beet, but again there would be conflict with other demands in regions that are already water-scarce (El Chami et al. 2015). Irrigation of higher-value vegetables and potatoes later in the season is likely to take precedence (Gibbons & Ramsden 2008; El Chami et al. 2015).

Adjustments to sowing date are not thought to be able to mitigate yield losses arising from a general reduction in rainfall in southern England (Cho et al. 2012), although they might allow avoidance of occasional, severe summer droughts (see below) (Butterworth et al. 2010). Similarly, it has been suggested that breeding for changes in phyllochron or grain filling duration are unlikely to improve wheat yields in southern England, but manipulating traits that control the effect of water stress on leaf senescence and biomass accumulation, such as canopy expansion, photosynthetic efficiency, and acquisition of water by roots, could improve grain yield under drought in UK wheat (Dickin et al. 2009).

Approaches that could potentially offset the decrease of water availability are: water licence trading, better agronomic management for higher water-use-efficiency, increasing the efficiency of irrigation, and shifting potato production towards the west and north areas of the UK (Daccache et al., 2011).

2.3 Atmospheric CO_2 Concentration

Increasing atmospheric CO_2 concentration has a direct effect on crop production through increasing photosynthetic efficiency, which results in accelerated biomass production. This effect is greater in C3 crops than in C4 crops, such as maize. Thus increasing CO_2 concentration is predicted to increase the yield potential of wheat (Wheeler et al. 1996; Ghaffari et al. 2002; Ewert et al. 2005; Stratonovitch et al. 2012), oilseed rape (Evans et al. 2010), potatoes and sugar beet in the UK. Indeed, the increase in CO_2 concentration is generally predicted to compensate for any yield-loss of wheat due to higher temperatures shortening developmental phases (Harrison & Butterfield 1996; Wheeler et al. 1996; Ghaffari et al. 2002; Richter & Semenov 2005; Cho et al. 2012).

2.4 Extreme events

The frequency and magnitude of extreme weather events are predicted to increase in the future. These include drought, waterlogging and both high and low temperatures. All these stressful conditions impact negatively on crop yields. The combined effects of greater variability in climate and frequency of extreme weather events is likely to increase variability of annual crop yields. There are however, a range of actions, depending on the crop, that could lessen the severity of effect.

The frequency of drought is predicted to increase in the UK. As indicated above, irrigation will be in competition with other demands and high-value crops are likely to take precedence. A judicious choice of crops in any year might be considered based on sufficient advance warning. Earlier sowing or choice of earlier varieties of crops such as oilseed rape, potato and sugar beet has been proposed as an option to avoid occasional severe droughts (Wolf 2002; Richter et al. 2006). Similarly, earlier sowing and grain filling of cereals, such as wheat, in a warmer climate would avoid severe summer droughts, but the probability of heat stress around flowering is predicted to increase significantly and reduce cereal yields considerably (Semenov, 2007, 2009). It has been suggested, therefore, that breeding strategies should focus on tolerance to high temperature rather than to drought per se in UK cereals (Semenov, 2009).

Waterlogging will become an increasingly serious problem in years of high rainfall. Flooded arable land causes large reductions in yield and potential crop failure. Good maintenance of field drains and management of surface water flows in and around fields can help alleviate the problems. There was some switching from winter- to spring-sown cereals in response to the recent very wet conditions of 2012. However, there appears a lack of research on the effects of high rainfall on UK crops and little effort to breed varieties that can withstand saturated and waterlogged soils. Based on the 2012 and 2013 cropping years, agriculture can therefore expect reductions down to 75% of the ten-year average yield if waterlogged conditions persist during the maturing, harvesting and sowing phases.

Frost is already commonplace, especially in the north. Winter crops are already hardy. They usually suffer a reduction in green area over the winter, but generally recover. A safeguard is offered in sowing at higher densities that are still compatible with maximum yield. High-value crops are increasingly protected by fleece or plastic. The main potential impact on crop yield could be late, severe frost on spring sowings and plantings. But generally, low temperature is likely to have less effect that too little or too much water.

Unusual weather is a normal feature of agriculture globally. Perhaps the greatest problem to be overcome is the lack of experience in the UK with drought and flooding, in both research and management. The interactions between too little or too much water with declining soil quality, associated effects on trafficability and land suitability for different crops need much more study.

2.5 Ozone pollution

The projections of ozone (O_3) over the major agricultural areas of the Northern Hemisphere showed significant increases of annual mean surface O_3 (Dentener et al., 2005). O_3 enters the leaves via the stomata during the process of gas exchange and can cause several symptoms such as chlorosis and necrosis. Young plants are more susceptible to O_3. Experimental evidence showed that O_3 tends to reduce yield although there is no agreement in the quantified amount of reduction. Overall, dicot species are more sensitive to reductions due to O_3 than monocot species (Heagle, 1989). Generally, there is little relevant literature on the effects of O_3 on UK crop production.

2.6 Responses of crops – summary and comment

Since the late 1980s, studies using mechanistic physiological models indicate small effects on crop yield of the projected changes in temperature and carbon dioxide concentration. In future dry climates, yield will be limited more or less in proportion to the water available. Within-year prediction and management of yield losses in such circumstances can learn from the considerable experience of dryland crop production in other countries. In future wet climates, yield may be limited by a combination of effects of too much water on crop plants and an inability to get on the field to harvest and cultivate. There is less experience that can be directly transferred from other countries to help understand and manage such situations. Years with unusual weather will continue to occur, as they have in recent decades, and *in principle* provide opportunities for research to assess physiological and agronomic causes and to develop responsive strategies.

Most studies listed here are based on well-researched physiological responses of crop plants to weather variables. Great care should be taken to avoid making, or taking notice of, forward projections based on associations between yield and climate during times when yield is being strongly affected by other factors such as general intensification. The projections of much larger and unrealistic increases in yield due to temperature made in the

UK Climate Change Risk Assessment of 2012, as criticised by Semenov et al. (2012) are a case in point.

3 BIOTIC FACTORS

3.1 Weeds

Weeds have negative effects by taking from the crop through competition for resource, and positive effects in supporting the arable food web (Marshall et al. 2003; Hawes et al. 2010). Assessing the effect of climate on weeds faces similar issues to those of crops in terms of a changing background. Two major trends have occurred over the past century independently of climate.

The first trend is that new weed species have appeared in the flora and have increased in population size and distribution so as to have economic effects. For example, *Veronica persica* and the north American *Epilobium* species and hybrids both first appeared a little over 100 years ago and are now among the common in-field weeds (Marshall et al. 2003; Heard et al. 2003; Hawes et al. 2005). Also, the absence of grass leys from most arable fields has encouraged the rise of annual volunteer weeds such as oilseed rape, wheat, oat, barley and potato. Though not detected in the UK arable seedbank before the 1990s, volunteer oilseed rape has become among the top 10 most frequent weeds of arable fields (Begg et al. 2006; Debeljak et al. 2008). A further change has been the rise of grass weeds in recent decades because of the prevalence of cereal crops: *Poa annua* is now by far the commonest seedbank species (Heard et al. 2003; Hawes et al. 2010); and black-grass *Alopecurus myosuroides* has become more problematic as herbicide-tolerant forms have evolved (Stratonovich et al. 2012).

The second trend is the reduction in beneficial arable plants due to intensity of cropping, to the extent that of any component of the UK flora, the arable has shown the greatest negative change in the latter half of the 20th century (Preston et al. 2002; Marshall et al. 2003). Most of these declining species are broadleaf weeds that cause little detriment to the crop but benefit by supporting the food web and recycling minerals.

The physiological effects of small climatic shifts on weeds will be similar to those on crops. For example, a rising mean temperature will shorten the life cycle of determinate forms, but extend it for indeterminate. But arguably, weed populations will be able to adapt more rapidly than crops since the main species consist of many genetically distinct variants that are highly phenotypically variable (Begg et al. 2012). Climatically induced shifts in weed populations are unlikely to have major effects compared to those that have occurred and are still occurring due to introductions, intensification, a changing arable sequence and resistance to herbicide.

3.2 Pests and diseases

There is a strong positive correlation between crop production and observed pest numbers (Bebber et al., 2014) and there is estimated to be an overall 2.7 km yr^{-1} (+/-0.8) northwards shift in crop pests and pathogens since 1960 (Bebber et al., 2013). This is associated with climate change, particularly rising temperatures, but also trade and biosecurity (Fisher et al., 2012).

Simple climate matching indicates that many pests and pathogens might extend their range, particularly northwards in the UK. Pathogens such as some of the cereal rusts and aphid-borne viruses would be expected to become more problematic if their epidemiology is limited by single dominating climate variables such as temperature. Various models predict changes in range and incidence of specific pest problems (Jaggard et al. 1998; Butterworth et al. 2010; Evans et al. 2010).

However, for many pathogens it is a combination of factors and non-linear relationships that determine epidemics and these will be very difficult to simulate in models (Butterworth et al. 2010). Detailed spatio-temporal modelling of fusarium head blight on wheat, for example, shows that occurrence is likely to decrease with climate change due to changes in rainfall and crop phenology, whereas a simplistic temperature-based model would predict an increase (Skelsey & Newton, 2015).

Simulations of future disease risk must be taken with caution, because different climate models and downscaling methods are used to make the projections and this can create considerable uncertainty.

Experimentation based on single factor changes in climate predict increases and decreases for pathogens with different modes of pathogenicity, but also many exceptions too, so no general rules prevail. Moreover, combinations of factors can result in effects on disease that cannot be predicted from these single factor results (Mikkelsen et al., 2014), while combinations of factors can influence host resistance and phenology in genotype-specific ways (Ingvordsen et al., 2015).

Another major factor that will affect future disease patterns is changes in the cropping patterns and in the crops themselves. Disease resistance is an obvious trait whether deployed in established or new crops, as is the diversity of resistance types and their deployment. Crops can also accentuate disease problems for others. For example, the increase in the maize crop in the UK substantially increases the fusarium head blight risk in cereals, especially wheat, by increasing inoculum. However, this problem may have been enhanced by the shift in fusarium species distribution.

There are many mitigation options including adapting agronomic factors such as timing of sowing, cultivar choice, cultivation methods, nutrition and management of crop debris. Management should consider avoidance of inoculum build-up as well as of epidemiologically-favourable conditions. The utility and durability of sources of resistance can be protected and enhanced by managing both spatial and temporal heterogeneity at a range of scales from within a crop to the landscape (Gregory et al., 2009; Newton et al., 2011; Chakraborty & Newton 2011).

3.3 Soil microbiota

The effects of climate change on soil biota are covered under a separate LWEC report card within the biodiversity section (de Vries and Bardgett). Effects of climate change on soil are likely to be particularly pronounced in arable soils. Erosion of arable soil is already sensitive to frequent soil disturbance (through tillage) and periods where soil is left without cover. Likewise plant driven effects are likely to be more pronounced under standard arable systems due to near monoculture. The effects of arable practice on soil communities is also likely to exacerbate effects described in de Vries and Bardgett; for example disturbance and fertilisation may result in a shift in fungal/bacterial balance and skews in population structure and activity leading to, for example, relatively high proportions of nitrifying and denitrifying organisms and greater flux through the nitrogen cycle compared to natural systems (Galloway et al 2003, Colloff et al 2008, Xue et al 2013).

Many impacts of arable agriculture also tend to reduce the likely efficiency of beneficial groups through depression in population size or reduction in diversity leading to fragility in function. Potentially the best example here would be functional groups associated with nutrient provision such as mycorrhizal fungi and nitrogen fixing organisms (Helgason et al 1998, Berthrong et al 2014) but could potentially include other groups involved in, for example, phosphorus cycling.

The high level of control in the arable system can however present opportunities for soil manipulation to reduce negative impacts. Changes in fertilisation practice can provide an opportunity to store C through compost, slurry, biochar or other amendments. Shifts to reduced tillage may enhance fungal groups such as mycorrhiza and curtail losses of soil and pollutant. There are contradictory findings as to whether reduced tillage can increase C storage (e.g. West and Post 2002) or result in redistribution of C (e.g. Sun et al 2011). More over, the crop plants themselves can be selected or managed to manipulate the system through direct or indirect means. For example, biological nitrification inhibition has been demonstrated to be effective in pasture systems providing a route to reduce leaching of nitrate and/or nitrous oxide emission (Subbarao et al 2013). As suggested in de Vries and Bardgett the effects of variable water supply and management can have significant effects of soil functioning which can have both direct and indirect effects on plant production. The loss of biological function in arable soil may therefore already be limiting the output of agriculture, consistent with evidence that plant root growth is likely limited by soil condition in a significant proportion of farms (Valentine et al 2012).

Critically, the understanding of soil is deficient due to its great complexity. There is consequently, a high degree of uncertainty in predictions and a difficulty in linking effects to specific climatic factors and management (Giles et al 2012). Additionally, experiments typically have to extend for long periods to ensure effects are not simply due to acute stress responses and to account for the inherent resilience of soil systems. Studies that combine aspects of management change with likely combinations of climate change scenarios are particularly lacking.

3.4 General biota

Organisms that inhabit the vegetation of the crop-weed layer and field margins form a food web that mediates several important ecological processes including comminution of plant and animal litter, predation and parasitism (which contributes to biocontrol of crop pests), pollination and the dispersal of seed and vegetative material. Some of these organisms, notably birds, butterflies and bees have iconic status as cultural biodiversity. The food web is strongly affected by field management, both through removal of dicot weeds and through direct impacts of pesticide and other aspects of field management (Hawes et al. 2009). As for weeds, the food web declined very greatly during the phase of intensification after the 1960s (State of Nature report 2013).

The degree to which shifts in temperature and rainfall are likely to affect these organisms is difficult to predict. Invertebrates generally respond to temperature much as determinate plants: a rise in temperature shortening the duration of development and therefore potentially increasing the rate of passage through a life cycle. However, the effects of small changes in temperature and rainfall are likely to be very small compared to continuing major trends due to management. The imperative is to regenerate the food web and its functions irrespective of climatic change; options include integrated management of crop-weed combinations, widespread establishment of species-rich field margins and improving the wider connectivity of the farmed habitat.

3.5 Biotic factors: summary and general considerations

The microbes, plants and animals of farmland have already been strongly affected over the last half-century by a range of influences, principally the intensification of cropping systems, such that any climatic shifts are likely to have only small further impacts. The imperative is to halt the declines in function and return the plant-soil system to a more resilient state. Any initial impacts due to change in temperature or rainfall could be stabilised or reversed as part of this process.

CONCLUSIONS AND RECOMMENDATIONS

Predicting the effects of climate on crop production should be considered in relation to major changes over the past 70 years in crop-areas, fertiliser, pesticide, tillage and yield. These changes were driven initially by national demands to achieve food security, then by global markets, environmental protection, macroeconomics and CAP and finally by the reliance on imports for food, fertiliser and animal feed.

Most experiments and predictions of the impacts of climate have been directed at, or based on, single crops, mainly wheat. The combined effects of temperature and CO_2 concentration on inputs and outputs in wheat and similar cereal crops are likely to be much smaller than the changes referred to above. Increasing incidence of dryness in the south of the UK is likely to cause the most systematic and important reductions of yield. Irrigation would help to maintain yield but will have to compete with other industrial and domestic demands for water. Effects of high rainfall in the north acting through saturation of soil and waterlogging are potentially as important as dryness in the south. However, the contributions of too much water suppressing plant growth directly and hindering field operations need to be distinguished and quantified. Some evidence is available from fluctuations in national yields around recent unusual weather patterns. The recent very wet autumn of 2012 and the highly favourable year of 2014 caused impacts on yield that should be considered moderate in a global context, that is less than a factor of 1.5 (i.e. between 0.7 and 1.5 of the ten-year mean yield).

Moreover, the emphasis in field research has been largely on crop growth and yield, and to a lesser extent on reduction in yield by disease. Pests (weeds, invertebrate pests and diseases) will be affected by changes in temperature and water, but the interactions between pests and crops are highly complex, non-linear and hard to predict. Given the range of pest species and intra-specific types and their known ability to evolve, pests in general are likely to adapt very quickly to climate change within the range of predicted scenarios.

The essential and beneficial biota of the soil and above-ground habitats are being reduced by continued intensification and inappropriate soil management. The additional impacts of climate are unclear but will probably be small in comparison to current trends. There have been few studies of effects of climate on other functional life forms such as weeds and soil biota that would enable a system-scale assessment.

Despite such major gaps in knowledge, there are many ways that agriculture can prepare to adapt to climatic change. Research should deflect attention from studies on single crop species to understanding how cropping systems might be returned to a sustainable state and made more resilient, whatever climatic shifts might occur. More generally, the following will reduce the susceptibility of crop production to unusual weather events and long term climatic trends: increasing the diversity of cropping through the number and choice of crops (both species and varieties) and economic crop products; stabilising crops and protecting soil through undersowing, mixtures and intercrops; implementing long term soil management to increase soil carbon, reduce compaction and prevent surface runoff; enhancing positive microbial associations in crop production, namely nitrogen fixing in legume crops and forages and mycorrhizal associations generally; breeding crop varieties that can cope with multiple stresses rather than just maximise yield or product quality under ideal conditions.

Food security is already a matter for concern in the UK. The country depends on imports of food, feed and fertiliser for its sustenance, while a large part of its produce is grown for industrial feedstock or exported. The gaining of food security will need a wholesale redirection of effort to grow more crops for local consumption on local resources.

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Appendix A. Data from government statistics

Government statistics were examined for trends (50-70 years) and short-term variations (5-10 year) in crop areas, inputs, yield and general outputs. Main sources were as follows: crop areas, UK government's *June Census*, available online in various summaries and formats; fertiliser, annual summary and some longer term trends in *Fertiliser Practice* published by Defra, available online for recent years; pesticide, Pesticide Use Surveys published by Defra and SASA, began 1974 as hard copy, conducted sporadically until the 1990s, and now available online every two years; yield and output, various including MAFF/Defra yearly summaries and *Financial Report on Scottish Agriculture*, recent issues available online but variously hard copy in earlier years. The data before the 1980s are mostly in hard copy reports (which were consulted for this review) and not available electronically. Information is very sparse for pesticides before 1974.