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5. Climate change impacts on horticulture

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EXECUTIVE SUMMARY

- The Horticulture sector is a plant-based sub-sector of the agriculture industry concerned with high value fruit, vegetable and ornamental crops. Horticultural production includes a very diverse range of crops, particularly when ornamental species are considered. Crops are field and orchard grown and also cultivated under protection (polytunnels and greenhouses).
- This study, considers the period up to 2050. By that time atmospheric CO_2 levels are predicted to rise to 550 ppm and mean global temperature to rise by between 1 and 2 ^oC (H)
- For some major crops such as cereals, increasing temperatures can reduce yield by shortening the time to reach maturity, whereas the acceleration of growth and development and extended growing season in root, leafy or perennial crops is likely to increase yield. The net impact of temperature and CO_2 will depend on the crop and the temperature shift but for a 1-2 ^oC increase would be positive for the majority of UK horticultural crops. (M)
- Periods of high summer temperatures (>30 ^oC) can have major negative effects on seed production, yield, quality and storability, particularly when they occur around the flowering and fruit development stages. Also, high temperature during early development can have major adverse effects on crop performance. Such episodes are likely to become more frequent in the future and pose an increasing risk to production. (H)
- For crops that overwinter, including perennial fruit crops and certain vegetable crops such as cauliflower, the exposure to a sufficient amount of chilling is essential for flower quality and subsequent development. The warming of the climate has already had an impact on fruit production and without mitigation by the industry (e.g. moving to less chilling sensitive varieties) future warming will negatively affect crop yield and quality because of insufficient chilling. The impact of reduced chilling will be higher in the south e.g. Kent than in the north e.g. Tayside. (H)
- In general, the warming of the climate will reduce the prevalence of frosts, although warmer winters could lead to reduced cold hardiness in perennial fruit crops, leading to more susceptibility to late frosts when they occur. Earlier flowering time might make the flowers more vulnerable to late frosts and also cause asynchrony with the normal pollinators resulting in poor fertilisation. (M)
- Reduced summer rainfall, coupled with increased temperatures, will result in increased evapotranspiration and soils will consequently be drier. Reductions in soil moisture will increase the requirement for water for irrigated crops. (H)
- Most soft fruit production now takes place in intensive protected systems with irrigation and between 70 and 80% of tree fruit and soft fruit production currently takes place in areas that are classified as being under water stress. Abstraction rates are predicted to rise by up to another 30% by 2050, which is likely to be an unsustainable situation. (H)
- Important long-season crops such as salads and vegetable brassicas are vulnerable to periods of drought that lead to dry soils, resulting in gaps in production. The most susceptible period to drought is around planting and crop establishment. A combination of reduced rainfall and warmer temperatures is likely to increase the probability of loss or interruption of production in such crops, particularly in the South and East of England. (H)
- Flooding and waterlogging prevents access to land for preparation for planting or for harvesting. In addition, crop growth is impaired because the soil becomes anoxic.

However, floods and waterlogging are intermittent events, which are not projected to become more frequent and thus overall are unlikely to prove an increasing risk to production. (M)

- Some pest invertebrate species will be able to complete more generations at higher temperatures and activity is likely to start earlier in the year. Warmer winters are likely to favour increased survival of some species. Extreme high temperatures and the increased frequency of heat waves will be deleterious to some pests. Warmer conditions may favour the survival and reproduction of migrant species such as *Plutella xylostella*. (H)
- The effects of changes in precipitation (drought or periods of heavy rainfall) on pest populations will depend entirely on the species and the timing of the event. Water-intolerant pests may prosper in periods of drought, whereas populations of slugs may decline. (H)
- Warmer winters are likely to improve survival of plant pathogens and higher average temperatures throughout the year will accelerate pathogen life cycles. (H)
- Presence of free water is very important for successful completion of the life cycles of many micro-organisms. For fungi, both infection and sporulation often require close to 100% relative humidity. Such conditions occur most commonly during the night and so a favourable night-time temperature can be critical. Models run for fungal pathogens of horticultural crops suggest that it is possible that the risk of infection will increase with climate change. (H)
- The impact of changes in weather conditions on weed growth is likely to be similar to that on crop plants. Some weed species may become more competitive as a result of the interaction between increased temperature and CO_2 levels. (H)
- The advent of milder winters and warmer summers, more typical currently of some other parts of Europe, has implications for the survival and reproduction of new pests, diseases and weeds. (H)
- Climate change may also affect the efficacy of current control measures. Control with pesticides can be affected by weather. The effectiveness of host plant resistance genes can break down under changed climatic conditions. (M)
- Natural enemies will have their own ‘climate ranges’, although these will not necessarily be the same as those of their hosts. There is insufficient information at present to make reliable predictions about the impact of climate change on natural enemies and the efficacy of biological control. (L)
- Insect pollinators, particularly honey bees and wild bees, are vital to maximising yield and quality in a number of horticultural crops producing fruit. For wild species, impacts of climate change are likely to occur at all levels of organisation including changes in phenology, declines due to narrower climatic niches, local or regional extinction, changing composition and functioning of pollinator communities and evolutionary change. Indirect effects, when climate change affects interacting species might be equally important. (H)
- The honey bee (*Apis mellifera*) is genetically diverse and has already adapted to a range of different climates around the world. However, populations are under considerable pressure from other stressors such as parasites and pathogens, which are changing over time, and it is hard to predict what the effect of the combination of these factors and climate change will be. (M)

INTRODUCTION

This report addresses the impact on horticultural crops, i.e. fruits, vegetables and ornamental species in the UK. Potatoes are not included in this report as they are considered in the report on ‘arable‘crops.

Over the earth’s history, the climate has undergone huge changes, driven by or linked to solar input changes, volcanic activity and the development of life forms. In the Holocene epoch, i.e. the period since the last major ice age, about 12,000 years ago, earth’s climate has remained relatively stable. For the majority of this period up to the middle of the 19th century, CO_2 levels in the atmosphere were consistently in the range 260-290 ppm. However, starting with the industrial revolution and amplified by increases in human numbers and consequent activity, that level has risen inexorably, currently being in excess of 400 ppm In the Northern hemisphere spring. CO_2 has risen at a rate of about 2 ppm since 1995 but other greenhouse gases (Methane and N_2O) are also increasing. For the purpose of this study, the relevant timescale is taken to be up to 2050. Beyond that time predictions of the climate and hence relevant adaptation strategies become increasingly uncertain. By that time atmospheric CO_2 levels are predicted to rise to 550 ppm and global mean temperature to rise by between 1 and 2 ^oC (IPCC, 2013).

This report deals with the edible, ornamental and amenity Horticulture sectors, which are plant-based sub - sectors of the agriculture industry. Edible Horticulture is concerned with high value fruit and vegetable crops that are used by people as a vital part of a healthy diet. The main tree fruit crops grown in the UK are apple, pear and plum, but there is a rapidly increasing area being given over to sweet cherry and some apricots are being grown on the Isle of Wight. Tree fruit crops are grown mainly in the South of England over a total area of about 18,000 ha. The main soft fruit crops are strawberry, raspberry and currant covering about 10,000 ha; much of it being grown under cover in regions of England and in Scotland. A diverse range of vegetable crops, including vegetable brassicas, carrots, leafy salads, onions and leeks are grown in a wide range of locations in England and Scotland over a total area of about 120,00 ha. This sector also includes protected crops, tomatoes, cucumber and peppers grown in glasshouses. The ornamental and amenity sector is an important economic area with a value in excess of £1 billion and a production area of about 12,000 ha (Defra, 2014). This sector includes Hardy Ornamental Nursery Stock (HONS), which is by far the largest of the groups, plus outdoor bulbs and flowers and protected ornamental crops. Horticultural crops are produced by specialist growers, who may also be sourcing products from overseas locations (Collier and Else, 2014).

Potential direct impacts of environmental change on these crops might be expected to include yield, reliable supply and quality, all of which are known to be responsive to environmental conditions that include temperature and water availability as well as CO_2 itself. Indirect effects would include altered vulnerability to pests and diseases as well as weeds and potential asynchrony with pollinators. A consequence of the diversity of horticultural crops is that environmental factors will have a combination of generic and crop-specific effects.

A proportion of the content of this report is based on the use of models of plant, invertebrate and pathogen development and reproduction. Many of these models have been developed to understand and make predictions about the life cycles and development of these organisms under different environmental conditions that might occur currently, but have also been used or extended to predict the effects of climate change. A few models have been developed specifically to address climate change. These models do not cover all species and a considerable amount of further research would be needed to achieve this. However, the approach taken by Thomas et al. (2011; 2014) in two projects commissioned by Defra showed that it may be possible to construct simple, but informative, models from the literature (provided relevant information is available) to make predictions about the impact of climate change on horticultural crops and on other agricultural sectors. The impact of climate change on horticultural crops has been considered recently in chapters in two books (Collier and Else, 2014; Dixon et al. 2014).

EFFECTS ON CROP YIELD, RELIABILITY AND QUALITY

Carbon Dioxide Impacts

Increases in CO_2 levels not only drive changes in the environment but also have a direct impact on plant performance through its role as a substrate for photosynthesis. Photosynthetic plants can be classified into C3 or C4 type organisms, depending on whether carbon is fixed directly in the same cells and at the same time as light energy is captured (C3) or whether a two stage process is involved where these processes are either separated within the leaf (C4, e.g. Maize) or at different times in the daily cycle (CAM e.g. Kalanchoe). All of the major UK horticultural crops are C3 plants and will show broadly similar responses to rising CO_2 with regard to photosynthesis.

Under the current conditions of approximately 400 ppm, C3 plants, which represent the majority of UK crop species, are limited in their photosynthetic potential by the atmospheric concentration of CO_2. Consequently, increasing the concentration of CO_2 has the potential to stimulate photosynthesis in these species. This is the rationale for using CO_2 – enrichment in glasshouses to enhance crop production. Atmospheric CO_2 enters the leaf by diffusion through stomata and is subsequently fixed in the leaf by the enzyme ribulose 1,5 bisphosphate carboxylase / oxygenase (Rubisco). Higher concentrations of CO_2 increase photosynthesis in two ways. Firstly, because the current CO_2 concentration is close to the K_m (the concentration that gives half the maximum rate of reaction) of Rubisco, increasing CO_2 increases the velocity of the carbon fixation reaction. Secondly, CO_2 competitively inhibits the oxygenase reaction of Rubisco, which, through the process of photorespiration, would normally reduce the efficiency of net carbon uptake. It is estimated that for a leaf temperature of 25 ^oC increasing atmospheric CO_2 concentration from current levels to 550 ppm, would increase Rubisco-limited photosynthesis by about 36% (Long et al., 2004). In practice, experiments growing crops at elevated levels of CO_2 show that this potential instantaneous increase in rates of photosynthesis is frequently not fully translated into increased yields as plants acclimate to the higher levels through a variety of mechanisms (Long et al., 2004).

Estimating the past impact of increasing CO_2 on UK horticultural crops is not possible, as it has taken place against a background of changes in varieties, technologies and growing locations and other climatic aspects. The information we have is based on experimental studies of responses to increasing CO_2. The range of studies on horticultural species under field conditions is somewhat less than those for cereals and forest trees but such studies consistently show an increase in photosynthesis, leading to increased dry matter or yields e.g. (Mortensen, 1994, Idso and Kimball, 1989, Chen et al., 1997, Chen et al., 2002, Wurr et al., 1998). It is difficult to predict the extent of yield increases to be expected as a consequence of future atmospheric CO_2 enrichment for three main reasons; firstly, the majority of enrichment studies have involved CO_2 levels between 600 and 1000 ppm, which are beyond those that may be expected in an industry-relevant timescale, secondly the acclimation responses of the different crops or even crop types vary depending on factors such as fertilisation, growth habit or sink capacity,(Wheeler et al., 2004, Bunce, 2001, Reekie et al., 1998), thirdly there are significant interactions between CO_2 levels and other environmental factors, especially temperature and water as will be discussed in following sections. With these provisos, it can be concluded that the effect of increases of CO_2 in the future are likely to have a positive effect on the growth and yield of horticultural species in the UK. Higher CO_2 can have impacts on plant composition and nutritional quality. Plants grown in high CO_2 tend to have lower levels of N and higher levels of soluble carbohydrates (Ainsworth and Long, 2005).

Temperature impacts

All regions of the UK have experienced increases in annual temperatures of between 1.0 and 1.7 ^{o}C since the middle of the 20th century and temperature increases are predicted to continue. For a medium emissions scenario, temperature increases in the 2050s are projected to be between 2.0 ^{o}C in Scotland and 2.8 ^{o}C in the South of England. For the winter, the projected range is 1.6 ^{o}C and 2.2 ^{o}C; again the greater increase being in the South of England. In addition to this general increase, the incidence and severity of heatwaves is predicted to increase (UKCP09, 2015). Both average increases and extremes can have significant impacts on horticultural crops.

The interaction between temperature and yield can be complex. For monocarpic crops such as cereals, increasing temperatures can reduce yield by shortening the time to reach maturity i.e. flowering and seed set (Wheeler et al., 1996, Moot et al., 1996). Similar effects may be seen with horticultural crops harvested at maturity such as onion (Daymond et al., 1997), whereas the acceleration of growth and development in root or leafy crops is likely to increase yield for a given harvest date (Wheeler et al., 1994, Pearson et al., 1997). As the increase in temperature will be accompanied by an increase in CO_2, which itself will have a positive impact on yield, the net impact of temperature and CO_2 will depend on the crop and the temperature shift. For the UK, which is a cool temperate climate, a net change of 1-2 ^{o}C net change is likely to be positive for the majority of horticultural crops but further increases in temperature are likely to have an increasingly negative impact as can already be seen in models based on warmer climates (Challinor et al., 2014).

Summer temperatures

In addition to the growth responses to average temperatures, unseasonably high or extreme temperatures are predicted to become more frequent. These can affect a wide range of crop production variables depending on the nature of the crop, stage of development or the time of year (see Table 1).

Table 1 Stages of development or traits for different horticultural crop types vulnerable to high summer temperatures. Modified from (Thomas et al., 2008).

Crop Type	**Examples**	**Vulnerable Process**
Annual vegetable crops	Brassicas, leafy salads	Planting, establishment, development, lifting or harvesting, quality
Perennial fruit crops	Apples, pears, cherries, soft fruit.	Bud break, flower initiation, flower development, fruit growth
Annual Protected crops	Tomatoes	Quality, yield

High summer temperatures can have major effects on yield and quality. They are a particular problem when they occur around the flowering and early fruit development stages and their effect is often carried through into loss of market quality (Morrison and Stewart, 2002, Ledesma and Sugiyama, 2005). Flower initiation and development are potentially sensitive stages in a wide range of crops. In tomato, high temperatures at the time of anthesis has a negative effect on fruit set by reducing the number of pollen grains and the viability of the pollen (Sato et al., 2000). High temperatures (30/20 °C day/night) during the growing season has a negative effect on pollen germination and pollen tube growth reducing cropping potential in everbearing strawberry and flower abortion post anthesis (Karapatzak et al., 2012, Wagstaffe and Battey, 2006).

High temperature during early development can have major adverse effects on crop performance. For example temperatures above 30 ^{o}C can inhibit germination in broccoli (Elson et al., 1992). Growers report that in the hot summer of 2006, there were difficulties with inhibition of vegetable brassicas, along with an increase in the incidence of blindness and buttoning.

In addition to their impact on crop yield and production, high temperature effects on reproduction will have a direct impact on seed production. Most seed is produced under protection in the EU but there already problems with extreme temperatures. The hot summer of 2006 led to shortages of certain varieties in 2007. For hybridisation, breeders rely on simultaneous flowering for both parents and plant at different times to achieve this. This has proved to be increasingly difficult in recent years (Thomas et al., 2008).

Extreme climate change events are likely to have less of an impact on crops, such as tomato, which are grown under protection when compared with those grown outdoors. Nevertheless, periods of high summer temperatures are likely to cause fruit/truss quality problems. For protected tomatoes, it is likely that there will be more erratic yields and increased wastage due to uneven ripening, soft fruit, poor/late set and delayed ripening of truss varieties (Thomas et al., 2011).

Winter temperatures

For crops that overwinter, which includes perennial fruit crops and certain vegetable crops such as cauliflower, the exposure to a sufficient amount of chilling is essential for subsequent development (see Table 2).

Table 2: Effect of potential impacts of warmer temperatures or insufficient chilling during winter on crop development after (Thomas et al., 2008, Atkinson et al. 2013).

Physiological impact	**Examples**
Cold hardiness limited	Apple
Early bud break and frost susceptibility	Apple, blackcurrant, strawberry
Impaired flower development and reduced yield	Apples, cherry, blackcurrant, strawberry
Delayed curd induction and lack of production continuity	Winter cauliflower

Many varieties of perennial fruit crops, such as apples, pears, cherries and blackcurrant and hops, require a sustained period of cold in the winter for vigorous flowering and fruit production (Atkinson et al., 2006). For apple, periods of low temperatures (<12 ^{0}C) are needed to induce dormancy in early winter and also a further period of low temperature (e.g. 1000 h at 6 – 9 ^{0}C) is required for dormancy release (Heide and Prestrud, 2005). In Golden Delicious, trees lower levels of budbreak were seen when high day temperature was greater than 14 ^{0}C (Naor et al., 2003). In 2001, there was an unusually mild winter in France. Subsequently, flower production was reduced. Many of the reproductive spurs developed into vegetative shoots and where flowers were formed they were small and deformed (Oukabli et al., 2003). The warming of the climate has already had an impact on fruit production and without mitigation by the industry (e.g. moving to less chilling sensitive varieties) future warming will negatively affect crop yield and quality because of insufficient chilling. The impact of reduced chilling will be higher in the south e.g. Kent than in the north e.g. Tayside (Atkinson et al., 2013). Spring flowering bulbs such as daffodil and crocus also require a period of winter chilling. Warmer winters and springs have resulted in them flowering much earlier than in the past. However, if winters become too warm, root initiation may fail. If this happened, bulb displays in the spring could disappear (Briscoe and Hadley, 2002).

Relatively small changes seen as earlier flowering time, associated with climate change have been identified by French researchers (Domergue et al., 2004). This might make the flowers more vulnerable to late frosts and also cause asynchrony with the normal pollinators and poor fertilisation. Susceptibility to late frosts after warmer winters would also be relevant for perennial amenity trees and shrubs, although the trends suggest that warmer winters are accompanied by fewer spring frosts and this will not be a common occurrence. A combination of warmer winters and high summer temperatures are likely to result in a trend to earlier planting dates for summer annual crops. This strategy may avoid high temperature damage to flowering but may also lead to increased losses due to late frosts.

Precipitation and Water effects

Water is likely to be a major factor in management decisions about growing horticultural crops in the future. Although central estimates of total UK annual precipitation show little change up to the 2080s even under high emissions scenarios, there are projected to be seasonal and regional variations, but with no simple pattern. The biggest changes in precipitation are predicted to be in the winter, with increases up to +33% on the Western side of the UK in contrast to the Scottish highlands, where a small decrease is predicted. Increases in the winter are offset by summer decreases of up to -40% in the South of

England, whereas small changes around zero are predicted for the North of Scotland (UKCP09, 2015).

Restricted water availability can have an adverse effect on yield and quality of many crops. Reduced rainfall, particularly in Southern regions in the summer is only part of the issue because increased temperatures will give increased ETp (evaporation) and soils will consequently be drier. Both Eastern and Western growing regions are predicted to become drier but the differences between the regions will be retained (Figure 1), placing particular pressure on the South East and Eastern regions water availability.

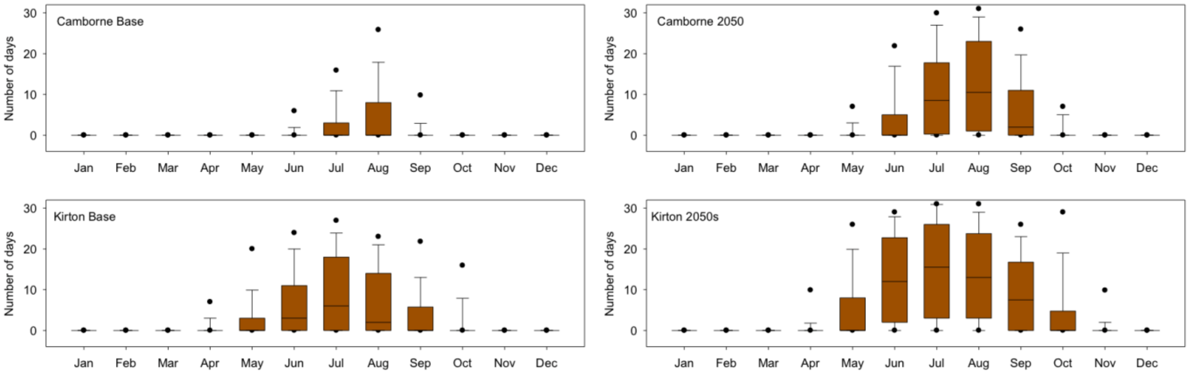

Figure 1. Annual cycles of dry soil for Camborne, Cornwall in the South West and Kirton, Lincolnshire in the East of England. Plots show Baseline (1960 - 1990) and 2050s time slices under a high emissions scenario. Plots show predicted number of days per month where soil is dry, defined as Soil Moisture Deficit is >20mm. Modified from Thomas et al., (2011).

The impact of reduced precipitation will vary with the crop. Some important vegetable crops e.g. Broccoli, are resistant to moderate water deficits when established (Gutezeit, 2006). Increases in atmospheric CO_2 lead to improved efficiency of water use by crops (Polley, 2002), which may partially ameliorate reduced water availability although in broccoli, it was observed that this effect was greater in well-watered plants than under restricted water conditions (Thomas et al., 2014). The problem of drought may be less critical for deep-rooted perennial crops such as Cider Apples where the industry can counter with appropriate management strategies such as the use of anti-transpirants and drought-tolerant rootstocks (Thomas et al., 2011). However, water shortage may be a bigger problem for trees in parks or heritage gardens, particularly in the south of England. Beech, for example, is known to be particularly vulnerable (Bisgrove and Hadley, 2002)

Reductions in soil moisture will be a problem for irrigated crops as the requirement for irrigation water will increase. This could have significant implications for soft fruit production, which has progressively moved to intensive protected systems so that most crops in this sector are now grown in this way. Protected cultivation is dependent on irrigation water and the demand has increased substantially in recent years and is predicted to increase in the future, particularly in response to warmer temperatures and extended growing seasons. Irrigation is also essential to achieve the quality demands of consumers and retailers (Thompson et al., 2007). Between 70 and 80% of tree fruit and soft fruit production currently takes place in areas that are classified as being under water stress (Knox et al., 2009) and abstraction rates are predicted to rise by up to another 30% by 2050 (Collier and Else, 2014), which is likely to be an unsustainable situation. Increasing stress on water availability is also likely to affect the choice and management of amenity plantings in vulnerable areas.

Extreme weather events

The most important of these are temperature (heat waves, frosts), water (drought, waterlogging) and storms (wind, hail / inundation). Most crops are vulnerable to storm and hail damage. These are likely to be more common in the future but it is not feasible to predict the occurrence of individual storms. Protection through netting may be available for outdoor perennial crops such as apple and cherry and soft fruit is being increasingly grown under glass or poly tunnel protection. For other crops strategies for minimising damage will include reducing risk by growing the crop across several geographically distributed planting sites (Thomas et al., 2008).

Horticultural crops can be vulnerable to different types of extreme weather. In general, the warming of the climate will reduce the prevalence of frosts, although as mentioned earlier, warmer winters could lead to reduced cold hardiness in perennial fruit crops, leading to more susceptibility to late frosts when they occur.

The impact of flooding and waterlogging lies in two areas. The first is that it prevents access to land for preparation for planting or for harvesting. This is important for all horticultural vegetable and salad field crops as well as fruit crops grown in the open. The second impact is that crop growth is impaired because the soil becomes anoxic. For vegetables, this can be fatal for young seedlings and reduce yield and quality for more established crops. Perennial fruit crops appear to be relatively resistant to short term waterlogging during the dormant season, which is where the greatest prevalence of flooding is found. The region most vulnerable to wet soil is the South-West and this is predicted to be the case for the 2050s. Overall, the predictions based on UKCP09 do not suggest there will be significant increases in the prevalence of days with wet soil in the future (Thomas et al., 2011). Rainfall increases are generally predicted for the winter in regions where the combination of rain and low temperatures already leads to a high incidence of wet soil.

Important long-season crops such as salads and vegetable brassicas are vulnerable to periods of drought that lead to bone-dry soils, resulting in gaps in production. The most susceptible period to drought is around planting and crop establishment. Predictions based on the LARS-weather generator (Semenov, 2007) indicate that the periods of summer drought, such as seen in 2006 are likely to become more prevalent in the future, especially in the South East of England (Thomas et al., 2008). The pressure on water resources in that region will limit the potential to alleviate the problem through irrigation.

Direct-drilled baby leaf salad crops are particularly vulnerable to both droughts and waterlogging. There are problems with conditions affecting land preparation and drilling, particularly when wet. The market for these crops is volatile and heavily weather-dependent. The harvest window for these crops is only 1 or 2 days whereas whole head can be cut earlier or later (Thomas et al., 2008).

EFFECTS ON PESTS, PATHOGENS AND WEEDS IN HORTICULTURAL CROPS

Virtually all cropping systems in the UK require a strategy to manage pests, diseases and weeds, although weeds are of little significance in soil-free protected cropping systems. With the possible exception of mammals and birds, the development of these pest organisms is dependent on the temperature of their surroundings and their life-cycles and survival may also be dependent on the amount and timing of precipitation. Horticultural production includes a very diverse range of crops, particularly when ornamental species are considered, and overall, horticultural crops are affected by a wide range of pest organisms. However, pests and pathogens tend to specialise in terms of the plant species they affect and so certain problems may occur in crops belonging to just one plant family or to a small number of families.

Pest organisms are monitored and controlled using a variety of methods, generally with the ambition of using an integrated control strategy. However, at present there is a strong reliance on synthetic pesticides. This is partly because of the lack of alternative methods of control for certain crop/pest/pathogen/weed combinations but also because of the high quality standards required of horticultural produce by retailers and their customers.

In particular, crops grown outdoors are exposed to a complex of pests and pathogens and associated organisms, including their natural enemies. These species display a range of dynamic interactions amongst themselves that will also be influenced by the crop and its environment. Climate change will have a range of effects on these many inter-specific interactions and it is certainly possible that small changes to a number of individual interactions, which we may be able to predict, will, in combination, to lead to significant changes in the structure of entire communities (e.g. Tylianakis et al., 2008), which, with the current state of knowledge, will be much harder to foresee.

Pest insects

The main groups of pest insect that infest horticultural crops grown in the UK are flies, moths and butterflies (larvae), beetles (adults and larvae), thrips, aphids and bugs. Both biotic and abiotic factors affect survival of insects and, in particular, extremes of temperature or rainfall can have a direct and considerable impact.

Effects of changes in temperature on pest insects

During most of their life-cycle, the rates of development of pest insects are dependent on temperature. Each species, and indeed each developmental stage within a species, has particular threshold temperatures which limit the temperature range within which development occurs (lower and upper development thresholds). These threshold temperatures, together with the low and high lethal temperatures, will broadly define the species' geographic range.

Some species of pest insect will be able to complete more generations at higher temperatures (provided the temperatures are below the upper development threshold) and species of pest aphid such as the peach-potato aphid (*Myzus persicae*) would be an example (Whalon and Smilowitz, 1979). For other species, factors such as an obligate winter diapause (diapause is a period of suspended development during unfavourable environmental conditions) may limit the number of generations a species can complete in year., However, more rapid post-diapause development in a warm spring would cause activity to start earlier in the year. Pest beetles of *Brassica* crops such as flea beetles and pollen beetles (*Meligethes* spp.) would be examples of species with a limited number of generations. These beetles overwinter as adults and complete one generation a year (Gratwick, 2012), although it is not clear from the literature whether diapause is obligate or facultative. Another example is the large narcissus fly (*Merodon* *equestris*) a pest of *Narcissus*, an important field-grown horticultural crop in the UK, which overwinters in the larval stage and also completes just one generation per year (Collier and Finch, 1992). Most pest species infesting UK crops spend the winter in the UK and their susceptibility to low temperatures depends on the resilience of the overwintering stage (which may be the egg (e.g. several species of aphid), larva (e.g. turnip moth (*Agrotis segetum*), pupa (e.g. several species of fly) or adult (e.g. cabbage whitefly (*Aleyrodes proletella*). The cabbage root fly (*Delia radicum*) overwinters in diapause as a pupa (Collier and Finch, 1983a) and can survive temperatures well below zero (this species is also a pest in North America), whilst species of aphid such as *M. persicae* that usually overwinter in the 'active' stages in the UK (adults and nymphs as opposed to eggs in diapause) can be vulnerable when the winter is cold (Bale, 2010).

In the future, the occurrence of very high temperatures and more frequent heat waves will certainly be unfavourable for the development of some pests which occur currently in the UK and, if the temperature is sufficiently high, this is likely to cause mortality. The exposure of certain species to very high temperatures may induce dormancy (aestivation) which will delay the following generation (Finch and Collier, 1985, Harrison and Barlow, 1972). Whilst the development of insects within their 'optimum' temperature range is often studied, the effects of temperatures above 30°C on species prevalent in temperate regions are not tested so frequently. As a result, there is a limited amount of information available on the possible effects of periods of very hot weather on pest insects in the UK.

Effects of changes in the amount of precipitation on pest insects

The impact of changes in precipitation (periods of heavy rainfall or drought) on pest insects will be dependent on the species and at which stage in its life cycle the event occurs. Pests which may benefit from periods of drought, include cutworms (turnip moth - *A. segetum*), which are moth larvae which can be damaging pests of a range of crops such as lettuce, red beet, carrot and leek. Wet conditions, as a result of heavy rainfall, appear to cause mortality of the first and second larval instars (Esbjerg, 1988).

Effects of changes in carbon dioxide levels on pest insects

Although insect phenology and abundance are strongly influenced by temperature and rainfall, insects may also be affected by the influence of environmental conditions on their host plants. Although an increase in the concentration of CO_2 may stimulate plant growth it can reduce the quality of host plants as a source of nutrition for insects (Lincoln et al., 1993).

Predicting the impact of climate change on pest insects

Mathematical models can be used to predict the phenology of particular species of pest insect. These range from quite 'simple' day-degree models, which are based on linear regression of the rate of insect development versus ambient temperature (e.g. Butts and McEwen, 1981, Pitcairn et al., 1992) to more complex process-based simulation models (e.g. Phelps *et al.*, 1993). Such models can be used, together with other information on insect abundance/survival, to predict the effects of climate change. Sources of 'future weather' data have varied depending on the model, where the predictions are for, and when the model was run. There is sometimes a problem with re-using some of the more complex models developed in the past because it may not be possible to gain access to the software. This may be for commercial reasons, because the developer has moved on or because the software has become obsolete. In addition, the parameters available for ‘projected’ weather conditions (e.g. UKCP09 scenarios) may not be the same as those that the model uses.

CASE STUDIES

Aphids

Most horticultural crops are colonized by one or more species of aphid and they are important pests because of the direct damage they may cause and also because they transmit plant viruses. Their life cycles, with both sexual and asexual phases and viviparity (internal development and birth of nymphs rather than the production of eggs) in their asexual phase enable aphids to increase their population size very rapidly when conditions are favourable. Some species are specialists, whilst others, such as *M. persicae*, are generalists and can be pests of a wide range of edible and ornamental crops.

A considerable amount of information is available about the effects of temperature on certain species of aphid and also about the predicted effects of climate change (Harrington et al., 2007a, Hullé et al., 2010). Considering species such as *M. persicae* which are able to overwinter in the UK as nymphs and adults (anholocyclic life cycle), warmer winter weather generally leads to a spring migration to crop hosts which is earlier than that following a cold winter (Harrington et al., 1990, 2007b). In addition, the abundance of alate aphids in the spring and early summer can be higher (Harrington et al., 2007a). This has been explained, in the case of *M. persicae,* for example, in terms of the level of cold tolerance by the anholocyclic clones of aphids which overwinter. After a severe winter few aphids will survive. Consequently population increase in the spring to the densities at which alate aphids will migrate to crops will occur later than following a mild winter when aphid survival over winter will be high (Bale, 2010). In the case of species that overwinter as an egg in diapause, often on a woody host (holocyclic life cycle) (e.g. currant-lettuce aphid (*Nasonovia ribisnigri*), lettuce root aphid (*Pemphigus bursarius*), willow-carrot aphid (*Cavariella aegopodii*)), warmer conditions in the late winter – early spring may also lead to earlier infestation, because they complete post-diapause development more rapidly.

Forecasts are available to predict the spring migration of several species pest aphid, although the structure of the forecasting model depends on how the aphid overwinters. The impact of climate change on their phenology and, in some cases, abundance, can also be predicted using these models. Overall, the expectation is that the date of capture in Rothamsted suction traps of the first alate aphid of the year will advance. Although the magnitude of the change will vary with species and location, it may be equivalent to an average of 8 days within 50 years (Harrington *et al.*, 2007a). In a study on *M. persicae*, the date by which the first alate aphid would be captured in the Rothamsted suction trap located at Kirton in Lincolnshire was estimated to be 9 and 20 days earlier by the 2020s and 2050s respectively, than the date predicted from the baseline data (26 May) (Collier et al., 2008). Overall, an increase in the mean temperature is also likely to lead to a greater number of generations and, as a result of this, a potential increase in population size.

Some species of aphid have developed resistance to certain insecticides and this is the case for *M. persicae* where individuals may be resistant to one or more insecticide groups. *Myzus persicae* with the resistance mechanism which leads to overproduction of the enzyme carboxylesterase may be resistant to more than one group of insecticides.

In the past, it was observed that towards the end of a growing season the proportion of aphids carrying the genes for this resistance mechanism increased, presumably as a result of selection pressure due to insecticide use. However, by the following spring, the proportion of resistant individuals had decreased considerably. Studies at Rothamsted Research showed that carboxylesterase resistance confers a fitness cost on overwintering *M. persicae* which makes them less able to survive winter conditions (Foster et al., 1996, 1997, 2002). Thus in this case, warmer winters as a result of climate change might lead to relatively greater overwintering survival of insecticide-resistant aphids. The fitness costs of other resistance mechanisms in *M. persicae* with regard to winter survival are less clear (Foster et al., 2002).

Flies

Fly larvae are pests of a number of horticultural crops. In particular, the larvae of several species of fly feed on the roots of widely-grown UK vegetable crops (cabbage root fly (*D. radicum*), carrot fly (*Psila rosae*), bean seed fly (*Delia platura*) and onion fly (*Delia antiqua*)). All overwinter as pupae in diapause and the carrot fly also overwinters as a larva on overwintered crops. Forecasting models have been developed for all of these species (e.g. Phelps et al., 1993; Sanborn et al., 1982; Liu et al., 1982). Whilst changes in winter temperatures would be expected to have little effect on overwintering survival (as the diapause pupae of all species are extremely cold tolerant and survive north American winters), climate change would be expected to impact on the phenology of these pests through earlier emergence in the spring and more rapid development during the summer period, leading to more generations each year. At least two of these species also respond to high summer temperatures by entering aestivation in the pupal stage (Finch and Collier, 1985, Collier and Finch, 1996). High summer temperatures and low soil moisture levels may also reduce survival of *P. rosae* (Vincent, 1999).

Collier et al., (1990) used a mathematical model developed by Phelps et al., (1993) to model the patterns of egg-laying by populations of cabbage root fly under different scenarios of future climate change. The output predicted that if the mean daily temperature increased by 3 °C, the cabbage root fly would become active approximately a month earlier compared with the baseline. In addition, it is likely that the emergence of flies from overwintering pupae would be less synchronised since, with higher temperatures in early spring, completion of diapause and post-diapause development would occur simultaneously in different individuals within the population. This is because of the wide inherent intra-population variation in the duration of diapause (Collier & Finch, 1983b). Despite this, there would still be just three generations of adults in a year, even in the south of England (in the UK there are currently three generations of adults in the south and two in the north). It was predicted that increases in mean temperature of 5 or 10 °C would lead to four generations each year and in these instances the pattern of egg-laying would be disrupted severely by aestivation (summer dormancy in the pupal stage).

The larvae of certain dipterous leaf miners appear to be becoming more abundant pests on particular vegetable and salad crops. These include *Scaptomyza flava* which is a pest of a range of brassicaceous crops, including rocket (Defra, 2011) and a relatively new pest, *Phytomyza gymnostoma,* which was first found in the UK in 2002*.* Whilst the basic thermal requirements to complete a generation are known (Shakeel, 2012, Kahrer, 1999) there is no information on the possible impact of climate change on either species.

Midge pests include swede midge (*Contarinia nasturtii*) and blackcurrant leaf curling midge (*Dasineura tetensi*). *Contarinia nasturtii* is a relatively minor and sporadic pest in the UK at present but it has increased in importance in Canada (Olfert et al., 2006), where there was also a study on the possible effect of climate change on this species (Mika et al., 2008). Mika et al. concluded that predictions of the potential for *C. nasturtii* to increase its distribution depended on the detail of the projections for climate change. This illustrates the value of using several climate change models, together with a range of scenarios, when predicting the possible spread of a pest as a result of climate change. Although there is a phenological model for *Dasineura tetensi* (Hellqvist, 2001), there is little information on the possible effects of climate change on this species and this is the same for most of the other pests of *Ribes* species (Mitchell et al., 2011).

The spotted wing drosophila (*Drosophila suzukii*) is a recent threat to crops of soft fruit in Europe, including the UK, (Calabria et al., 2012, Cini et al., 2012) and causes damage to healthy ripening fruit as well as previously damaged fruit. Phenological models indicate that there is the potential currently for *D. suzukii* to spread throughout most of Europe, and that the UK already has a suitable climate, but that with climate change it might also spread to Scandinavia (Cini et al., 2012). Warmer conditions would favour completion of more generations in a year, potentially making this an even more damaging pest.

Butterflies and moths

To predict the possible effect of climate change on the larva of the moth, *A. segetum* (cutworm), a pest of a range of horticultural crops such as lettuce, carrot, leek and beetroot (and also potato), Collier et al. (2008) ran a descriptive population model (Bowden et al., 1983) using 'synthetic' weather data. The model estimates the timing of egg hatch and development of the larvae to the third instar for daily cohorts of newly-laid eggs (the period of egg-laying can be estimated through using pheromone traps to monitor male moths, or by a day-degree prediction (Collier, unpublished data)). Larval survival in the first two instars is then predicted from daily rainfall. In the two locations 'tested', the predicted survival of larvae increased into the future (2020s and 2050s). With the exception of *A. segetum*, there have been relatively few specific studies on the possible effects of climate change on the pest Lepidoptera of horticultural crops which complete their entire life cycle in the UK, such as large and small white butterflies (*Pieris brassicae, Pieris rapae*) and codling moth (*Cydia pomonella*). However, in a study on a range of butterfly species in the UK in relation to climate warming, Roy et al. (2001) suggested that *P. brassicae* was the only species for which a considerable decline in abundance was predicted, whilst all the benign species of butterfly considered might increase or, for a few species, remain stable. *Pieris rapae* was not investigated in this context in the study. In a study to estimate the impact of climate change on the ranges of crop pest species in Europe, an increase of one generation per year was predicted for *C. pomonella* in northern regions of Europe (Svobodová et al., 2014**).**

The diamond-back moth (*Plutella xylostella*) is a globally-significant pest of *Brassica* crops. Currently, UK winters are too severe for many diamond-back moths to survive so migrants from continental Europe and further south lead to the most significant infestations each year (Chapman et al., 2002). Diamond-back moths, together with other migrant Lepidoptera, appear to come from the south and, as a result, will cover large distances over the sea. The direction of the wind, and wind at high altitudes in particular, will determine whether and when moths arrive (Chapman et al., 2002). In general, more migrant Lepidoptera have been arriving in the UK over recent years and a study by Sparks et al. (2007) showed that this increase is associated with increasing temperatures in south western Europe. The research indicated that 14 new species of moth or butterfly might be expected to arrive in southern England for every 1°C rise in temperature in south western Europe. Obviously, the majority of these migrant species will not be pests.

Collier et al. (2008) investigated the possible impacts of climate change in the UK on infestations of diamond-back moth using information from published studies on the relationship between development and temperature. Three different times for the beginning of egg-laying were used. To start with, it was assumed that most moths causing an infestation would be migrants and two scenarios were selected: with eggs laid on 1 June (close to the current situation) or with eggs laid one month earlier (earlier migration as a result of climate change). For the final scenario it was assumed that the diamond-back moth would overwinter in the UK in future and that, if it was warm enough, females would start laying eggs from 1 February onwards. The three scenarios indicated that as females started to lay eggs earlier, and as climate change projections further into the future were used, the diamond-back moth completed an increasing number of generations within a year. The diamond-back moth is notoriously difficult to control. This is because it has a relatively short generation time and because it has a propensity to become resistant to insecticides. Thus, if, as a response to climate change, the diamond-back moth starts development earlier and can complete more generations in a year, it is likely to be a much greater threat to UK crops.

Beetles

As indicated above, some of the key pest beetles of vegetable crops have only one generation per year and so the impact of climate change may be limited. The black vine weevil (*Otiorhynchus sulcatus*) is possibly the most economically important pest beetle of horticultural crops and can cause damage both to soft fruit and ornamental crops. Although the effect of temperature on development and reproduction of this species has been studied (Son and Lewis, 2005), there has been no specific study on the possible impact on this species of changes in temperature as a result of climate change in the UK. However, it is likely that warmer, drier summers would favour the insect, as warmer conditions mean that they can reproduce all year round. In a detailed study on the effect of elevated atmospheric CO_2 on feeding by *O. sulcatus*, increases in the concentration of CO_2 in the atmosphere (from ambient levels of 375–700 ppm.) reduced the numbers which were feeding on the roots of blackcurrant (*R. nigrum*) plants (Johnson et al., 2011).

Effects of climate change on other invertebrate pests

Non-insect invertebrate pests of horticultural crops include mites, slugs and nematodes. Mites are pests of fruit crops and protected crops, *Narcissus* and occasionally of outdoor vegetable crops such as runner bean. Infestations by spider mites are favoured by high temperatures and drought stress. Thus it is likely that climate change will have an impact on the two-spotted spider mite, *Tetranychus urticae,* which infests many crops. *Tetranychus evansi* is a relatively ‘new’ pest that is spreading through Europe and attacks important solanaceous crops including tomato.

Slugs are important pests of a number of edible and ornamental horticultural crops as well as arable crops. Options for slug control are limited currently and there are concerns about the impact on water quality of one of the pesticides used. Slug development and activity are favoured by high levels of moisture. Willis et al. (2006) used an individual-based model of *Deroceras reticulatum*, the most common pest slug, to investigate possible effects of climate change on slug numbers in the UK. Currently, the best conditions for *D. reticulatum* are in south-western England and north-eastern Scotland has the worst conditions. The UKCIP02 predictions were used to predict slug population dynamics in the 2020s, 2050s and 2080s, with two scenarios for emissions of greenhouse gases. The model runs indicated that locations where conditions are most favourable for *D. reticulatum* will move towards the north, from south-western England and Wales to northern Wales and western Scotland.

Thomas et al. (2011) developed a simpler model to estimate the number of days when slugs might be active. They used a threshold where ≥ 2 mm of water remained when the potential amount of water lost by evapotranspiration was subtracted from the amount of rainfall each day, and where there was a daily minimum temperature ≥ 5^oC. UKCIP09 projections were used to make the predictions. The results concurred with the study by Wills et al. in that they suggested that the higher amounts of rainfall occurring currently in Cornwall in spring and autumn provides more days which favour slug activity than in the two other locations investigated (Lincolnshire and Angus). The output indicated that the number of days favourable for slug activity would not vary much between the 2030s and 2050s, apart from a slight increase in the 2050s for Angus. Thus it appeared that there was no additional requirement to adapt control measures beyond those that are used currently (although these are not ideal at present).

Nematodes may cause damage to a range of horticultural crops, both directly and as vectors of virus. However, overall, there has been relatively little research on the potential impact of climate change on nematodes. Neilson and Boag (1996) investigated the possible impact of climate change on virus-vector nematodes in the UK, highlighting the difficulties of, for example, predicting whether changes in the amount and pattern of rainfall would alter nematode distribution on a large scale. They suggested that there might be up to a 200 km increase in the range of nematodes northwards for an average rise in temperature of 1 ^oC. Bearing in mind that the movement of nematodes through soil is very slow, there would necessarily be a time-lag before any impact was apparent. However, as dispersal is often through the intervention of humans and other vertebrates, it could be relatively rapid.

Plant pathogens

The main pathogens of horticultural crops are fungi, bacteria and viruses. The great, and wide, diversity of edible and ornamental horticultural crops grown in the UK means that consideration must be given to a range of pathogens. However, certain pathogens, such as *Botrytis cinerea* (grey mould) will infect a range of crops. Unsurprisingly, the amount of damage due to plant pathogens is affected greatly by the weather, especially temperature and rainfall (Evans et al., 2008). Some pathogens, particularly viruses, are disseminated by vectors such as aphids and nematodes, whose abundance and phenology are themselves affected by the weather.

Effects of changes in temperature on plant pathogens

Warmer winters are likely to improve survival of plant pathogens, partly through the impact of warmer conditions on their plant hosts, and, overall, higher mean temperatures during the year will accelerate the life cycles of pathogens. This will, for example, increase the efficiency of sporulation and infection by species of fungi which are foliar pathogens (Coakley et al., 1999; Harvell et al., 2002). The soil-borne fungus *Fusarium oxysporum f. sp. Cepae* infects the roots and basal plate of onion bulbs, leading to bulb rot. This fungus may also cause 'damping off' and may delay the emergence of onion seedlings. Based on the output from models for climate change it is suggested that this fungus may cause more significant problems in the future, (Cramer, 2000). This is because high temperatures favour fusarium basal rot, with the optimum temperature range being 28–32°C.

Effects of changes in precipitation on plant pathogens

The presence of free water is very important for successful completion of the life cycles of many micro-organisms. In the case of fungi, both infection and sporulation often require in the region of 100% relative humidity. Such high levels of humidity are likely to occur most often at night and so the temperature at night can be critical (Harvell et al., 2002). The development of disease is often as a result of an 'interaction' between temperature and wetness. For example, more favourable conditions of wetness compensated to a certain extent for less favourable temperatures and *vice versa* when pods or leaves of oil seed rape were inoculated with suspensions of spores of *Alternaria brassicae* (horticultural *Brassica* crops are also infected by this pathogen) (Hong et al., 1996). The lesions took the same amount of time to develop (4 days) after exposure to 12 h wetness at 15 °C as after 24 hours wetness at 10 °C. For scab (*Venturia inaequalis*) on apple, Mills and Laplante (1951) established the hours of wetness needed for ascospores to infect leaves, and at range of average temperatures, and this ranged from >48 h leaf wetness at 0.6-5.0 ^{o}C to 9 h at 16.7 ^{o}C.

Modelling the effects of climate change on plant disease

A number of approaches have been employed to model the effects of climate change on diseases of plants (Garrett et al*.* 2006). However, Scherm (2004) and Scherm and Coakley (2003) indicated that there were several difficulties associated with applying models to predict the effects of climate change on disease. For example, the inputs to the models have a high degree of uncertainty (as do climate change scenarios), and both the non-linear relationships and thresholds often defining the responses of pathogens to weather variables, make it difficult to collect enough data to produce a meaningful prediction. In addition, the potential for plants and pathogens (and vectors) to adapt is often ignored.

For fruit and vegetables, researchers have developed forecasting models for a number of important fungal pathogens e.g. *Sclerotinia sclerotiorum* (Clarkson et al*.* 2007), *Botrytis squamosa* (Clarkson et al., 2000), several fungal pathogens of *Brassica* (Evans et al., 2008, Minchinton et al. 2013), *V. inaequalis* and *Podosphaera leucotricha* on apple (Berrie and Xu, 2003, Xu and Robinson, 2005), *Botrytis cinerea* on strawberry (Xu et al., 2000) and *Peronospora destructor* (De Visser, 1998, Gilles et al., 2004). Some of these models are based on the type of information described for *A. brassicae* and *V. inaequalis* above.

However, despite the development of a number of forecasting models for key pathogens, there has been limited research on the impact of climate change on the pathogens which infect horticultural crops in the UK. One reason for the limited use of forecasting models to predict the impact of climate change may be that whilst the effects of free water are often incorporated into forecasting models by using data on leaf wetness (e.g. Minchinton et al., 2013), there is unfortunately, no simple method to estimate leaf wetness from the data on rainfall or relative humidity produced as outputs by a number of climate change models. Thus it appears to be more difficult to integrate pathogen models with climate models than it is for insect models, to predict the effects of climate change on disease.

Phoma (*Leptosphaeria maculans*) is one exception. This is a fungal pathogen of oil seed rape and other *Brassica* crops, although it is currently relatively unimportant in horticultural *Brassica* crops. Models to describe the development of epidemics of phoma stem canker were based on field data and used temperature and rainfall data as inputs (Evans et al., 2008). The predicted start, in the autumns of 2020 and 2050, of leaf spotting by phoma was respectively 5–10 or 10–15 days earlier than in the period 1960–1990 (used as a baseline). The relatively 'small' differences from the baseline were because the start of leaf spotting depends on both temperature and rainfall and the effects of decreased summer rainfall counteracted the effects of increased summer temperature. However, there was predicted to be a large effect of climate change in spring on the date of initiation of phoma stem canker, with dates predicted to be as much as 80 days earlier than in 1960–1990.

Effects of climate change on dispersal of plant pathogens

Climate change may also affect the dispersal of pathogens. For example, the spores or other propagules of many pathogens are dispersed by rain splash (e.g. Pielaat et al., 2002). An alteration, as a result of climate change, in the distribution, intensity and frequency of rainfall events may affect such dispersal.

For pathogens, such as plant viruses, which are dispersed by invertebrate vectors, the effect of weather conditions on the phenology and abundance of the vector is important (discussed above for aphids which are common vectors of plant viruses). Changes in temperature may have further effects on the interaction. For example, the retention time on aphid mouthparts of non-persistently-transmitted viruses can be affected by the ambient temperature, which could have implications for virus spread (Jurik et al., 1987). The survival of viruses during the winter will depend on the abundance and condition of their overwintering hosts and how well their vectors survive.

Increases in temperature may cause the ranges of pathogens and their vectors to expand, which could bring pathogens into contact with larger numbers of potential hosts and provide new opportunities for pathogens to hybridise (Garrett et al., 2006). Additionally, the effect of globalistion on pathogen dispersal, by increasing the movement of humans and goods, may act synergistically with temperature changes.

Effects of changes in carbon dioxide levels on plant pathogens

Higher concentrations of CO_2 may affect a plant host and its pathogens in many ways (Coakley et al., 1999) and some of the effects of higher concentrations of CO_2 on plant diseases may counteract others. The higher growth rates of plants which are grown under higher concentrations of CO_2 may result in canopies which are more dense, leading to higher levels of humidity that will favour pathogens. The lower rates of plant decomposition observed when CO_2 concentrations are raised may increase the amounts of crop residues on which pathogens can overwinter, which would lead to higher levels of inoculum at the start of the growing season. The growth of pathogens themselves may be affected by higher concentrations of CO_2, leading to greater production of fungal spores. However, increased concentrations of CO_2 may also lead to physiological changes in the host plant, which might increase the resistance of the host plant to pathogens.

Evolution of pathogens

The extended growing seasons that are likely to result from higher temperatures should provide more time for the evolution of pathogens (Garrett *et al.*, 2006). The evolution of pathogens may also be more rapid when they are abundant, so that increased rates of survival (in winter and/or summer) may contribute. The occurrence of climate change may also help to determine whether pathogen populations will reproduce sexually or asexually. The overwintering of sexual propagules may be favoured by a change in ambient temperatures, thereby increasing the evolutionary potential of a pathogen population.

Case study

Calleja (2011) developed models for three different diseases affecting the UK strawberry industry. These were powdery mildew (*Podosphaera aphanis*), grey mould (*B. cinerea*), and strawberry black spot (*Colletotrichum acutatum*). *Podosphaera aphanis* and *B. cinerea* are the two most common diseases affecting the UK strawberry industry whereas *C. acutatum* has become widespread in the UK quite recently. The models were then run with inputs from the UKCP09 scenarios across four different timescales (Baseline, 2020, 2050 and 2080), and three different emission scenarios (low, medium and high). The inputs were temperature and rainfall/relative humidity, depending on the pathogen.

Incidence of *P. aphanis* was predicted to increase across most of Britain, with disease incidence increasing more in Scotland, west Wales and northern England and with a progressive increase in incidence from 1990 to 2080 across most of Britain. Almost all of the cases where an increase in incidence of *P. aphanis* was predicted were due to an increase in the number of occasions where the summer temperature fell within the optimum 15 – 27 ^{o}C range. Incidence of *B. cinerea* was predicted to change across most of Britain, with increases north of the Midlands and slight decreases elsewhere, particularly in the south. Where increases in incidence were predicted, the most rapid increases were until 2020, falling back by 2050 and 2080. The key factor leading to increased incidence was an increase in occasions when the optimum temperature conditions were achieved, particularly for regions where *B. cinerea* is currently limited by low temperatures, such as in Scotland and northern England. Beyond 2020, the continued increase in temperature was accompanied by a decrease in occasions when the optimum rainfall and humidity levels occurred, leading to a decline in disease incidence. Incidence of *C. acutatum* was predicted to increase drastically across most of Britain; increasing most in Scotland and along the west coast of Britain. Increases to 2080 were observed in these same areas, whilst the Midlands and south east of Britain experienced an increase in disease incidence only until 2020. Where an increase in disease incidence was predicted, this was due to an increase in occasions where the temperature was in the optimum range for development of the disease.

One of the outcomes of the probabilistic projections for all three pathogens was the increased variability between climate projection runs when compared to the baseline. This was for all projections for all locations, implying that whilst the median number of outbreaks will increase in most of Britain, the actual number of outbreaks from year to year could vary considerably, from years with very low disease outbreaks to years with potential epidemics. This was to an extent that was not seen during the baseline years.

New pests and diseases

In spite of extensive national and international restrictions and procedures, new, invasive, pests and pathogens do establish and spread. These 'new' species will also respond to climate change, with both ecological and economic implications (*e.g.* Hellman et al*., 2008). The likely occurrence of milder winters and warmer summers, which are more typical at present of some other parts of Europe, will have implications in relation to the survival and subsequent reproduction of new pests and pathogens. Non-indigenous pests and pathogens may establish first in protected crops under glass and then move to outdoor crops, as and when conditions are favourable. As mentioned above, the spotted wing drosophila is a very new threat to soft fruit crops in Europe (Calabria et al., 2012) and has been found quite recently in the UK (J. Cross, personal communication). It is possible that novel crops grown in the future may be hosts and sources of pests and pathogens that are new to the UK and some of these pests and pathogens may have host ranges that include crops grown currently in the UK.

Effects of climate change on the ability to control pests and diseases

Most of the economically important pests and pathogens in the UK are managed through combinations of monitoring and forecasting, pesticide applications, host plant resistance (where available), cultural controls (such as rotation) and good husbandry. It is fairly obvious that climate change could also affect the efficacy of the control measures used currently.

The weather can affect the application and performance of pesticides. High temperatures are reported to reduce the effectiveness of some pesticides (Paiva et al., 1995, Palm, 1975) and increase others (Grafius 1986, Yadwad and Kallapur 1988, Zhu et al*.,* 2006). The efficacy of certain pesticides may also be altered by the level of humidity (Imai et al*.,* 1995), or by the amount and timing of rainfall after pesticides have been applied (Suss et al*.,* 1994). The occurrence of rainfall can also determine whether a grower can apply a treatment at the time of most need. For example, wet conditions may encourage the development of a particular pest or pathogen, but prevent the application of sprays.

It is well known that pest and pathogen populations can themselves develop resistance to chemical pesticides or other control measures. The ability of a pest or pathogen to 'resist' a particular treatment may carry a fitness cost, which might be influenced by climate change. For example, as described above, *M. persicae* individuals with esterase-based resistance to insecticides are less likely to survive a cold, wet winter (Foster et al*.,* 1997; Foster et al*.,* 1996).

The number of active ingredients available to control pests and pathogens has decreased in recent times, at least partly due to changes in EU pesticide legislation, and this reduction may continue. The limited range of control options for some crops may be conflated with the effects of climate change through, for example, the reliability of forecasting systems, the impact of an increased number of pest and pathogen generations on selection for pesticide resistance and the number of days suitable for pesticide application during critical periods.

There are a number of instances where sources of genetic resistance to pests and pathogens have been identified and incorporated into plant cultivars that are grown commercially e.g. resistance in lettuce to *N. ribisnigri*. There are situations where the effectiveness of such resistance genes has broken down under changed climatic conditions. For example, there is a range of examples of the breakdown of resistance at high temperatures (e.g. Kuginuki et al., 1991, Huang et al., 2006, Li et al*.,* 2006, Ellis et al*.,* 1994, Eisbein and Haack 1985) and changes in humidity might also influence this breakdown (Wang et al*.,* 2005).

To date natural enemies have not been used to a great extent in fruit, field vegetable or ornamental crops grown outdoors, although natural enemies are used extensively and effectively in protected crops and are considered to make a contribution to pest control within agroecological farming systems (Crowder et el., 2010; Phillips et al., 1994). Natural enemies will obviously be constrained by their own 'climatic requirements', but these may not be identical to those of their hosts (Campbell et al., 1974, Islam and Chapman 2001). Climate change may not affect certain natural enemies to the same extent/in the same direction as the pests they are intended to control. For example, Dunn (1952) showed a difference between the influence of temperature on the feeding rate of a predatory ladybird, *Coccinella septempunctata,* and the rate of reproduction of a prey species, pea aphid (*Acyrthosiphon pisum*). Above a temperature of 10 ^{o}C, the rate at which the ladybird consumed the aphid exceeded the reproduction rate of the aphid, whereas below 10 ^{o}C the numbers of aphids built up more quickly than they could be consumed by the predator.

As stated at the beginning of this section on pests, pathogens and weeds, crops grown outdoors are exposed to a complex of pests and pathogens and associated organisms, including their natural enemies, with many inter-specific interactions. 'Natural pest control' undoubtedly makes a contribution to crop protection, although often not to the level required by the market. Climate change will have a range of effects on the individual species in these complexes, and their interactions, which may alter the 'services' that natural enemies deliver. However, with the current state of knowledge, it is impossible to predict the outcome with regard to the pest and pathogen complex in any particular cropping system.

There is increasing interest in the use of biopesticides, including products based on microbial control agents (fungi, bacterial toxins, viruses and nematodes) to control plant pests and pathogens in horticultural crops. For example, biopesticides based on entomopathogenic fungi have been used for inundative control, akin to the use of chemical pesticides. Temperature, humidity, sunlight and other factors can affect both efficacy following application and persistence on plants and, similarly, soil type/soil moisture interactions, temperature, and a range of biotic factors can affect performance in the soil (Jaronski, 2010). The resistance of a host and its ability to recover, and the virulence of the pathogen and its ability to replication, can alter considerably with sometimes very small changes in temperature and such responses may not be linear or easy to predict since they are the result of complex 'genotype x genotype x environment' interactions (Thomas and Blanford, 2003). Thus although a good deal of research has been undertaken, it is likely that there is insufficient information at present to make reliable predictions about the impact of climate change and this underlines once more how difficult it will be to predict how climate change will affect the extremely complex web of biotic interactions occurring in crops grown outdoors.

Effect of climate change on weeds

Competition from weeds is a considerable challenge to horticultural production. The species range is similar to those infesting arable crops and indeed many field vegetable crops are grown as part of an arable rotation. The particular challenge for most growers is the lack of effective methods for controlling weeds, particularly in relation to herbicides. This is due to the withdrawal of certain active ingredients (as a result mainly of EU legislation), the relatively small market that weed control on horticultural crops provides for agrochemical companies and the low rate of discovery of 'new' herbicides.

In the UK, the impact of changes in weather conditions on weed growth in terms of temperature, precipitation and extreme events is likely to be similar to that on crop plants. With regard to the potential impact of climate change, Neve et al. (2009) suggested that there are two key questions: 'How will climate change affect crop-weed competition' and 'What is the potential for agricultural weeds to rapidly adapt to changing climates?' Obviously for both questions the outcome will be species-dependent but there is, for example, a suggestion that competition from C3 weeds could be greater following climate change, as a result of elevated levels of CO_2 (Ziska, 2000). In addition, elevated levels of CO_2 have been shown to increase the dominance of invasive species in natural communities (Smith et al., 2000). Climate change may also lead certain species to expand their ranges and may change the phenology of reproduction and other processes (Neve et al., 2009). It is likely that 'native' weed species are already well-adapted to climate stresses and that there is a considerable amount of genetic variation in native weed populations that allows them to adapt to changing conditions.

Changes in the weather may also affect the ability of growers to control weeds with herbicides for the reasons described for pest and disease control. Widespread use of herbicides has led to selection over time, conferring phenotypic resistance which allows certain weeds to survive and reproduce in the presence of herbicides. There is a lack of studies which address systematically the impact of climate change on the evolution of resistance to herbicides (Busi et al., 2013).

EFFECTS ON POLLINATORS

Insect pollinators are vital to maximise yield and quality in a number of horticultural crops producing fruit (e.g. apple, pear, plum, cherry, tomato, courgette, runner bean etc.). Insect pollinators may also be important for production of seed for a range of edible and ornamental species, a large proportion of which will be undertaken outside the UK. Bees are regarded widely as the most important pollinators and include the domesticated European honeybee (*Apis mellifera*) (Carreck and Williams, 1998). A number of other species, such as the buff-tailed bumblebee (*Bombus terrestris),* have been domesticated to provide crop pollination services (Delaplane and Mayer, 2000), which in the UK includes protected crops such as tomato. It was estimated that in 2007, insect pollinated crops covered about 850,000 ha in the UK (Breeze et al., 2011), with much of this being crops of field beans and oilseed rape. By region, south east England had the greatest area of insect pollinated crops due to the relatively large amount of fruit production. Analysis of honeybee hive numbers suggested to Breeze et al. that managed honeybees may provide only up to a third of UK crop pollination services and that wild bees may contribute considerably more to UK crop pollination services than thought previously. Indeed, many wild bees can pollinate plants more effectively than honeybees (Thompson and Goodall, 2001). In addition, some species of wild bee appear to be less sensitive to 'poor' weather conditions (temperature and wind speed) than honeybees (Rogers et al., 2014).

In a review of the status of pollinator populations, Potts et al. (2010) considered that the effects of climate change would occur at all levels of organisation including changes in phenology, local or regional extinction, changes in the structure and functioning of pollinator communities and evolutionary change. In addition to these direct impacts, there could be indirect effects through the impact of climate on interacting species (plants, natural enemies, pathogens) might be equally important. For example, lack of winter chill can reduce the effective pollination period of some fruits which if combined with limitations in pollinator activity (cold, wind and rain) can induce limited fruit set.

In a study on the effect of climate change on honeybee populations Le Conte and Navajas (2008) pointed out that this species has already shown high adaptive potential as it is found all over the world and in a range of different climates. This is due to considerable genetic diversity within the species and the evolution of geographic races that are adapted to specific environmental conditions. This genetic diversity will be key to future adaptation to climate change. However, honey bee populations are also under considerable pressure from other environmental stressors such as parasites and pathogens, and possibly insecticides, which are themselves changing over time and it is hard to predict what the effect of the combination of these factors and climate change will be (Godfray et al., 2014).

Conclusions

Horticultural crops encompass a wide variety of species and crop types with a range of production systems, seasonality, environmental sensitivities and pest and disease susceptibilities. Assessing the likely impact of climate change on this sector is therefore a complex activity, particularly as the UK climate is not uniform, with a significant range of temperatures and precipitation from north to south and east to west. The main changes that can be anticipated are increases in the atmospheric level of $CO_{2,}$ increasing temperatures, changes in the pattern of precipitation and more extreme events (heatwaves, storms and droughts). These can have positive or negative impacts, depending on the crop and the extent and timing of the change. Based on the analysis in this report, Table 3 lists what we judge to be the most significant potential impacts and the confidence in the predictions.

Table 3: Potential impacts of climate change on UK horticultural crop production. Confidence levels are indicated as high (H), medium (M) or low (L).

Potential Impact	Confidence level
The net impact of temperature and CO_2 on yield will be positive for the majority of UK horticultural crops.	M
Periods of high summer temperatures are likely to become more frequent in the future and pose an increasing risk to production.	H
Without mitigation by the industry, future warming will negatively affect fruit crop yield and quality because of insufficient winter chilling.	H
Earlier flowering time might cause asynchrony with the normal pollinators resulting in poor fertilisation.	M
Reductions in soil moisture as a consequence of reduced summer rainfall and increased evapotranspiration will increase the requirement for crop irrigation.	H
Most tree fruit and soft fruit production, which is increasingly dependent on irrigation, takes place in areas that are under water stress, which is likely to be an unsustainable situation.	H
More frequent droughts and heatwaves increase the probability of loss or interruption of production of long season salad or vegetable crops.	H

Floods and waterlogging are unlikely to prove an increasing risk to production than at present.	M
Some pest invertebrate species will be able to complete more generations at higher temperatures and activity is likely to start earlier in the year. Warmer winters are likely to favour increased survival of some species.	H
Extreme high temperatures and the increased frequency of heat waves will be deleterious to some pests.	H
Warmer conditions may favour the survival and reproduction of migrant pest species such as *Plutella xylostella*.	H
Water-intolerant pests may prosper in periods of drought, whereas populations of slugs may decline.	H
Warmer winters are likely to improve survival of plant pathogens and higher average temperatures throughout the year will accelerate pathogen life cycles.	H
Models run for fungal pathogens of horticultural crops suggest that it is possible that the risk of infection will increase with climate change.	H
Some weed species may become more competitive as a result of the interaction between increased temperature and CO_2 levels.	H
Climate change may reduce the efficacy of current pest and disease control measures.	M
There is insufficient information at present to make reliable predictions about the impact of climate change on natural enemies and the efficacy of biological control.	L
Insect pollinators may be affected in a number of direct and indirect ways by climate change	H
The honey bee (*Apis mellifera*) is under pressure from stressors such as parasites and pathogens, and it is hard to predict what the effect of these factors together with climate change will be.	M

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