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The impact of global warming on plant diseases and insect vectors in Sweden

Jonas Roos[1], Richard Hopkins[2], Anders Kvarnheden[1] and Christina Dixelius[1,*]

[1]Department of Plant Biology and Forest Genetics, Uppsala BioCenter, SLU, Box 7080,
SE-750 07 Uppsala, Sweden
[2]Department of Ecology, Agricultural Entomology Division, SLU, Box 7044, SE-750 07 Uppsala, Sweden
[*]Corresponding author, E-mail: Christina.Dixelius@vbsg.slu.se, Phone: +46 (0)18 673234, Fax: +46 (0)18 673389

Cold winters and geographic isolation have hitherto protected the Nordic countries from many plant pathogens and insect pests, leading to a comparatively low input of pesticides. The changing climate is projected to lead to a greater rise in temperature in this region, compared to the global mean. In Scandinavia, a milder and more humid climate implies extended growing seasons and possibilities to introduce new crops, but also opportunities for crop pests and pathogens to thrive in the absence of long cold periods. Increased temperatures, changed precipitation patterns and new cultivation practices may lead to a dramatic change in crop health. Examples of diseases and insect pest problems predicted to increase in incidence and severity due to global warming are discussed.

Key words: Agricultural crops, Climate change, Pathogens

Introduction

The Swedish winter of 2009–2010 was unusually cold and one with plenty of snow. However, in the northern hemisphere it was generally warmer than normal. The first decade of the 21st century was actually the warmest on record (NASA 2010; SMHI 2010). It is clear that the climate is changing and the temperature is projected to undergo a relatively high rise in Sweden compared to the overall global mean change (Hansen et al. 2006; SMHI 2010; Leijonhufvud et al. 2010). Climate change will have a very diverse affect on agricultural production and cultivation practices in different parts of the world. Even on the European continent a large variation exists in climate conditions, soils, cultivation practices, land use and not least in political and economic conditions. Several models and projections of climate change impacts on future food production and food security are available (Tubiello et al. 2007; Ziska & Bunce 2007; Gregory et al. 2009; Soussana et al. 2010). Highlighted factors are: increased impact of already present insect pests and pathogens, introduction of new species due to global trade and travel, and extreme weather phenomena. If suitable conditions exist, establishment and long-term survival of such pests and pathogens may occur, especially in combination with new crops, weeds and altered cropping systems. In addition, there are effects of elevated levels of greenhouse gases, although ironically increased CO_2 content in the atmosphere is expected to increase the yield of many agricultural crops by 5 to 15% (Olesen & Bindi 2002; SJV 2007). However, CO_2 fertilization in climate impact models is an uncertain factor (Long et al. 2006), and predictions made from climate chamber experiments may differ from those based on treatment of plants in field conditions (Leakey et al. 2009). Future challenges include sustained food production for an increasing world population, greenhouse gas mitigation and carbon sequestration practices. The future scenarios may also hold many unpredicted impacts, for example interactions between abiotic and biotic stress components. In this paper we report on the current understanding and expected events in a geographic region where agricultural production today is accomplished on its northern margin. The emphasis is on crop health and does not include emerging infectious diseases on animals or other husbandry related constraints (Nielsen et al. 2010; Randolph & Rogers 2010).

Meteorological data

The overall agricultural production in Scandinavian countries is restricted by three main components: the length of the vegetation period, the number of days with temperatures below 0°C, and the extremely long day light conditions. For example, Sweden is a country that covers a distance of 1574 km, from latitude 55° N (Smygehuk) to 69° N (Treriksröset), with the most southern parts corresponding to southern Alaska (Helmfrid 1989). However, due to the close proximity to the warm Gulf Stream in the Atlantic Ocean, the winters are much milder than similar latitudes in for example Siberia and Canada. Climate conditions vary from temperate in the south to polar in the north. Obviously, most of the agriculture production is located in the southern provinces and central plain regions, along coastal lines, lakes and rivers. Roughly three million hectares are used for farming, which is a factor of 7.3 less than land area used for forestry (SCB 2010). In many Swedish regions with small farms, agriculture and forestry production are tightly linked to secure income. The vegetation period ranges from 250 days in the south to 160 days in the north, where the latter includes extra hours from the midnight sun period north of the pole circle during the summer months. Precipitation is evenly distributed throughout the year and ranges from 500 mm in central regions to more than 1000 mm in the western and alpine regions. The alpine regions may receive extensive quantities of rain and snow, whereas in contrast, the Swedish east coast along the Baltic Sea can suffer from long periods of drought (Rummukainen et al. 2004). It is worth emphasising that 80-90% of the Swedish agricultural production is located south of similar activities in Finland (Peltonen-Sainio et al. 2009).

Changes in vegetation period

The Intergovernmental Panel on Climate Change (IPCC) reports (2007a; 2007b), which were based on different greenhouse gas emission scenarios, predicted increases in temperature and altered precipitation patterns. The highest temperature rise is expected in the northern latitudes. An estimated temperature increase in Sweden of 4°C one hundred years from now, implies that the geographic temperate zone would move northwards by between 500 and 800 kilometres (Fig. 1). In such a model, the temperature in southern Sweden would correspond to the current conditions in France or northern Spain, and the central part of Sweden would correspond to climatic conditions similar to those in southern England or northern Germany (SOU 2007). Thus, the length of the vegetation period (mean daily temperature > +5°C) would increase by one to two months, or as much as three months in the most southern part of Sweden (IPCC 2007b; SJV 2007; Fågelfors et al. 2009; Peltonen-Saino et al. 2009). In should be pointed out that besides length of growing season and solar radiation, late spring and early autumn frosts are the present main constrains for crop production (Olesen & Bindi 2002). Rainfall patterns would also change, leading to dry periods during the summer in the southeast, compared to an increase of rain on the West Coast. However, the overall envisaged change in precipitation involves a significant exchange of snow to rainfall and an increase of the latter during wintertime. Such environmental changes will also impact a number of soil quality related factors that will be reflected in levels of crop yields and crop health. One important, but often neglected process, is extensive and escalating mechanical damage incurred to roots and lower plant parts upon repeated freezing and thawing which is one expected future scenario. If not lethal, small and large wounds will provide excellent opportunities for pathogens to enter crop plants. Furthermore, the predicted variation in winter temperatures poses a number of physiological stresses on the plants which current winter varieties cannot withstand (Olesen et al. 2010), calling for new breeding efforts. For a thorough description of expected climate changes and particularly their bearing on Swedish agriculture and cropping systems, see the report by Fågelfors et al. (2009). Obviously, this anticipated environmental shift impacts the extent of plant diseases and insect pests, both presently occurring and introduced new species.

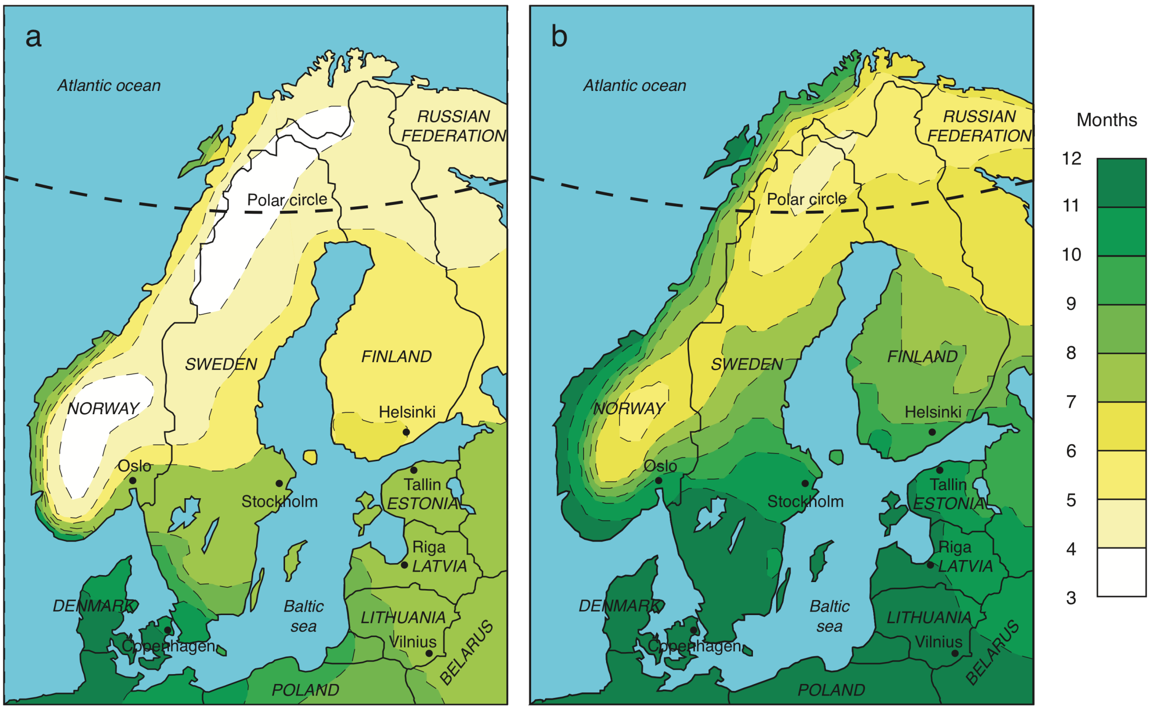

Fig. 1 Number of months with a mean 24-hour temperature above +5°C for the years 1961–1990 (a) and 2070–2100 (b) visualizing an annual move of the zones northward of 5 to 8 km. The map is based on predictions made by SweClim (Rummukainen et al. 2004; Kjellström et al. 2005). Despite this rapid change, temperature sums, extreme long-day conditions and sporadic cold winters will restrict introduction or northerly expansion of new crops or cultivars like soybean, sunflower and winter cereals, unless extensive breeding efforts are made. Another important aspect is the influence from intensive agricultural activities on the Baltic Sea, which already today is severely constrained mainly due to nutrient leakage.

New regulations

Sweden and other Nordic countries have so far been protected from a range of plant pathogens and insect pests, leading to comparatively low use of chemicals to control such problems (SJV 2010; KEMI 2010) compared to Central and Southern Europe (Eurostat 2010). This phenomenon is mainly due to the long period of low temperatures during the winter that kills off or reduces the survival of pathogenic microorganisms and insect pests. Also, the geographic isolation of the Scandinavian Peninsula from the European continent plays a protective role. New challenges and opportunities in this region are to adapt to longer growing seasons comprising at least 2-3 harvests of hay or silage, expansion of winter varieties, less ploughing, and the introduction of new crops. Together with changed precipitation patterns, future cultivation practices present a thriving environment for pathogen and insect attacks.

Sweden must in the near future pay attention to the EU directive 2009/128 on integrated pest management (IPM), to be integrated in Swedish legislation by December 2011 and implemented in practice from January 2014. According to the goal stipulated in the new IPM regulations, a number of disease, pest and weed preventing actions must be taken in combination with reduced levels of agrochemicals in order to minimise effects on human health and ecosystems. There are regulatory frameworks on plant protection in place on various levels, in Sweden represented by the Swedish Board of Agriculture. Since most threats are known, it is of utmost importance to have action plans prepared well in advance of occurrence of new plant diseases and insect pests. In this context, efficient monitoring and early warning systems must be in place and should be coordinated regionally, between neighbouring countries. But there is also a need to establish long-term monitoring data sets to detect potential changes in prevalence, phenology and adaptation to new environmental conditions followed by risk assessments. Exploring archive materials has shown great potentials in this context to dissect different environmental components and their impacts on plant pathogens (Bearchell et al. 2005; Shaw et al. 2008)

Projected major plant health problems

It has been put forward that diseases and pests will be more favoured than crops due to changed environmental conditions and prolonged growing seasons in Sweden and Finland (Fågelfors et al. 2009; Peltonen-Sainio et al. 2009). Plant diseases and pests that are expected to increase in their importance are summarised in table 1. However, there are uncertainties in this prediction and several unexpected problems may occur. Also, whether new resistance breeding efforts will be successful is unclear. A milder climate will in general favour insects and thereby also a range of virus diseases. Various rust diseases (brown, yellow) on wheat and barley are expected to increase due to the extended growing seasons (SJV 2007) and more aggressive strains might be introduced, e.g. stem rust on wheat (Chakraborty et al. 2010). Willows grown for biofuel are also expected to face increased leaf rust (*Melampsora*) problems (Karnosky et al. 2002; Rönnberg-Wästljung et al. 2008). Not all plant diseases are expected to cause significant damages. For example, scald (*Rhynchosporium secalis*), powdery mildew (caused by different fungi within the Erysiphales) and Septoria leaf blotch (*Mycosphaerella graminicola*) are predicted to decrease in importance in areas with dry summers (SJV 2007). However, the future impact of leaf blotch diseases is difficult to foresee but it may become important in northern areas concurrently with the moving limit of cultivation and increase of humidity. Similarly, snow mould fungi and other pathogens causing over wintering diseases will decrease in importance due to milder winters and less snow cover (SJV 2007).

Late blight on potato

Presently, late blight caused by *Phytophthora infestans* is the most serious plant health problem on potatoes in Sweden. Chemical spraying can take place up to every fifth day under favourable seasonal conditions, in order to protect plants from infection. During the last 20 years, late blight epidemics have changed significantly in Europe. This has been explained by a rapid spread of a new *P. infestans* population from Mexico during the 1970s, now allowing sexual reproduction to occur (Fry et al. 1993). Recent epidemiological studies have shown that A2 mating types are spreading faster than A1 (www.euroblight.net). These new populations also have a greater capacity for spore production, with the result that more sporangia (asexual spores) are produced per unit area of infected leaf. Another feature is the shorter interval between infection and the appearance of symptoms (the so-called latent period). The latter implies a need for shorter intervals between fungicide sprayings to prevent infection. The co-existence of the two mating types enables oospore formation and thereby soil infection (Andersson et al. 2003), making the pathogen even more difficult to control. High proportions of the A2 mating type are mainly found in the Nordic countries and in other European areas with cold winters (Hohl and Iselin 1984). It has been suggested that freezing temperatures in soil may prevent the degradation of oospores, resulting in an early peak of infected potato tubers by oospores germinating early in the season (Widmark et al. 2007). One of few long-term studies on plant diseases in Scandinavia has been done in Finland where data on late blight incidence and epidemics from 1933 to 2002 were compiled (Hannukkala et al. 2007). More frequent and earlier epidemics recorded in this dataset were linked to favourable weather conditions. During this time span, the disease was

Table 1. Major pathogens, viruses and insect pests expected to increase in importance in Sweden due to milder climate.

Crops	Disease agent	Comment
Brassica crops	*Altenaria brassicae*	Higher humidity and milder winters favours the black spot disease[1]. An increase of mycotoxins may occur[2].
	Leptosphaeria maculans	Establishment of a sexual stage promotes virulent strain development[1,3,4].
	Meligethes aenus	Pollen beetles are well established and the number of generations/year is expected to increase[5].
	Plutella xylostella	Diamondback moth may increase in importance[6].
	Aphids/*Beet western yellows virus*	Warmer climate will favour the main vector *Myzus persicae*[7].
Cereals	*Erysiphe graminis*	Expected to increase, especially in winter cereals[7].
	Fusarium graminearum *Fusarium* spp	Fusarium wilt and head blight on cereal crops. In particular, an increase of grains with high mycotoxin levels might be a consequence of a more humid climate[5,7,8].
	Ramularia collo-cygni, *Pyrenophora tritici-repentis*	Ramularia leaf spot will increase together with other leaf spot diseases like tan spot disease[7,9].
	Ustilago maydis	Corn smut is expected to occur due to increased acreage of maize[1].
	Diabrotica virgifera	Western corn beetle, not yet present in Sweden, but occurs in neighbouring countries[10].
	Oscinella frit, *Mayetiola destructor*	Frit fly and Hessian fly are expected to increase in winter cereals[7].
	Ostrinia nubilalis	European stem borer is presently the most important pest on maize on the European continent[11] and *Sesamia nonagrioides,* the pink stem borer, has occasionally been found in Sweden. Both borers may become established in Sweden[5,12].
	Aphids/*Barley yellow dwarf virus*	Expected to increase due to a warmer autumn[7,13].
	Bymoviruses and furoviruses	Soilborne viruses in cereals not yet present in Sweden, but may be introduced[14].
	Psammotettix alienus/*Wheat dwarf virus*	Expected to increase due to a warmer autumn[7].
Potato	*Alternaria solani*	Early blight is predicted to increase in regions with more frequent dry periods, interrupted by heavy showers[15].
	Phytophthora infestans	Oospores survive winter climate. High rate of sexual reproduction[5,16].
	Leptinotarsa decemlineata	Colorado beetle is not yet present in Sweden but occurs in neighbouring countries[7].
	Aphids/*Potato virus Y*	Problems with PVY in seed production may increase as a result of larger aphid populations[7].
	Spongospora subterranea/*Potato mop-top virus*	The virus vector thrives in humid climate[17].
Sugar beet	*Cercospora beticola*	Expected to increase in moist areas[1,7,15].
Tomato	*Bemisia tabaci*/begomoviruses	*Tomato yellow leaf curl virus* and vector may become established in greenhouses[18].

Sources: SJV (personal communication)[1]; Nawaz et al. (1997)[2]; Evans et al. (2008)[3]; Evans et al. (2010)[4]; Fågelfors et al. (2009)[5]; Gregory et al. (2009)[6]; SJV (2007)[7]; Walter et al. (2009)[8]; Walters et al. (2008)[9]; Hummel et al. (2008)[10]; Malvar et al. (2004)[11]; Trnka et al. (2007)[12]; Habekuß et al. (2009)[13]; Kühne (2009)[14]; Vereijssen et al. (2007)[15]; Widmark et al. (2007)[16]; Santala et al. (2010)[17]; Botermans et al. (2009)[18].

spread as far north as latitude 65° N. A consequence of this is that the future production of certified disease-free seed potatoes is at high risk. In a climate change perspective, increasingly earlier and warmer springs, together with slightly warmer summers and more humid conditions – collectively resulting in more indistinct seasons – is predicted to favour late blight incidence in the future. Chemical sprayings on potato to prevent late blight is already today by far the largest chemical input in Sweden on a single crop, thus, a further increase is not welcomed. Unfortunately, there are presently no efficient alternatives to control this disease, since *P. infestans* constantly overcomes efforts by breeders to improve the resistance (Fry 2008).

Soilborne diseases

Some biotic constraints are easier than others to foresee, since they are emerging in neighbouring countries. But what about soilborne pathogens causing diseases such as Verticillium wilt (*Verticillium* ssp), take-all (*Gaeumannomyces graminis*), clubroot *(Plasmodiophora brassicae)* and various rots (*Sclerotinia sclerotiorum, Aphanomyces euteiches*) that already are well established in various Swedish regions? The current view is that a prolonged season and changed soil temperature profiles will incite larger losses to these pathogens than today (SJV 2007; Evans et al. 2009). To address these questions, a Swedish soil archive dating back to the 1950s is currently being analysed to find links between pathogen prevalence, meteorological variables, crop rotation schemes, yield and nutrient status of the soil (Jonsson et al. 2010). There is also some indication that the *Sclerotinia* life cycle may change; following mild winters, a pre-seasonal sclerotial stage has been observed in France and Germany leading to more frequent root infections on oilseed rape (Evans et al. 2009). Another interesting observation is that plants infected by soilborne pathogens are generally more sensitive to above ground pathogens, exemplified by the *Verticillium longisporum – Leptosphaeria maculans* interaction on oilseed *Brassica* crops (Staal 2006).

Furthermore, many economically important plant-infecting viruses are transmitted by soil-living organisms, such as plasmodiophorids, fungi and nematodes. The diseases caused by these viruses are especially difficult to control, because the vectors cannot be controlled by chemicals and they may form resting spores containing infectious virus. Increased soil moisture and temperature in temperate regions, including northern Europe, are expected to increase the activities of zoospores and nematodes that transmit viruses (Jones 2009). *Potato mop-top virus* (PMTV) and *Beet necrotic yellow vein virus* (BNYVV) are transmitted by the plasmodiophorids *Spongospora subterranea* and *Polymyxa betae*, respectively. Both of them have recently been introduced into Sweden and are now spreading (Rydén et al. 1986; Sandgren 1995; Lennefors et al. 2000; Santala et al. 2010). The most important factor for this spread is probably the movement of infected plant material and soil, but climate factors may also have been involved. Bymoviruses and furoviruses (transmitted by *Polymyxa graminis*) are of great economic importance in autumn-sown cereals in large parts of Europe (Kühne 2009), but have not yet been reported from Sweden. These viruses are nonetheless likely to be introduced sooner or later and their spread may be facilitated by the expected climate changes.

Insects and viruses

There are two distinct mechanisms by which climate change can impact the relationship between pests and crop plants. Firstly, changes in climate have a direct impact on the biology of insects, including vectors, leading to differences in their survival, reproduction and spread. Secondly, there are the likely changes in agricultural practice that will take place as a result of climate change, and the influence of these changes on the availability of host plants for the pest species; e.g. the introduction of new crop species and plant genotypes, and changes in husbandry practice.

Insects cause damage and crop loss in a range of ways, and are mostly associated with the direct impact of their feeding in the form of yield loss and fall in harvest quality due to cosmetic damage. However, sucking insects, such as aphids, are also associated with the transmission of viruses, which can lead to major economic crop losses. The insect transmission of plant viruses can be classified as persistent, semi-persistent or non-persistent. Persistent transmission requires sustained feeding by the insect, while non-persistent transmission is dependent on a more superficial relationship between the insect and the plant.

Amongst the insects that are commonly associated with virus transmission, aphids are of particular interest in the Nordic region for a number of reasons. Aphids generally have a low developmental temperature threshold and a short generation time, so that when they continuously reproduce in a parthenogenetic manner they achieve 18 generations a year in British conditions (Harrington 1994; Harrington 2007). Yamamura and Kiritani (1998) suggested that aphids are amongst the insects best adapted to take advantage of a warming climate, and could go through an extra five generations a year following a warming of 2°C. Others have suggested that besides increases in CO_2 concentration, differences in soil nitrogen content and population density also play a part for aphid abundance (Newman et al. 2003), but nevertheless they are expected to increase in importance as pests in Sweden (Fågelfors et al. 2009). Aphids show a considerable variation in their life-cycle traits, and even within species variation can be very high. Some species, termed holocyclic, respond to the oncoming winter with a sexual phase, often placing eggs on woody plants. Anholocyclic aphids on the other hand, do not go through the sexual phase and continue with parthenogenetic and viviparous reproduction throughout the year. Some species are a mix of holocyclic and anholocyclic clones. Within a species, the proportion of individuals that are holocyclic tends to be greater in colder regions, as the eggs resulting from sexual reproduction are very much more cold-hardy than the active, viviparous forms which persist year round in anholocyclic clones.

Research from Poland suggests that there has been a radical reduction in the proportion of holocyclic clones of some aphid species in recent years (Ruszkowska et al. 2010). If this trend is reflected in Sweden, then aphids may soon be reproducing asexually all year round. This biological change may take place simultaneously with man-mediated changes in the availability of host plants. Autumn sowing for example will become more common, and autumn sown cereals have doubled in acreage in Sweden from 1981 to 2009 (Svensson 2010). This leads to the risk of a so-called "green bridge", when winter crops may emerge sufficiently early to receive insects migrating from maturing crops, which can be especially important for vectors such as aphids and the transmission of virus.

Warmer autumns and winters will increase the risk for insect transmission of viruses into winter crops, such as winter wheat, winter barley and winter oilseed rape. They are now sown when the number of active insect vectors has decreased significantly. *Wheat dwarf virus* (WDV) is transmitted in a persistent manner by the leafhopper *Psammotettix alienus*. Already at the beginning of the last century (1912, 1915 and 1918), a disease presumed to be caused by WDV severely affected wheat in central Sweden (Lindsten & Lindsten 1999). It has since then periodically damaged winter wheat in the central parts of Sweden. The periodic re-appearance of the disease has been associated with changes in agricultural practices (Lindsten & Lindsten 1999; Lindblad & Waern 2002). The host range of WDV includes many common grasses, and a recent study has shown that grasses growing in vicinity to WDV-affected wheat fields are infected (Ramsell et al. 2008). These grasses may act as a long-term reservoir for the virus. The leafhoppers acquire WDV from infected volunteer plants or grasses and then transmit the virus into winter wheat at the beginning of the autumn. They overwinter as nymphs and in spring, wingless nymphs transmit WDV from the infected wheat plants in the field (Lindblad & Sigvald 2004). A study in Sweden showed that the catches in autumn of adult *P. alienus* in fields of winter wheat increased with higher temperatures. During weeks with an average maximum temperature below 10°C only few leafhoppers were caught in yellow water traps, but during weeks above 10°C, the numbers increased with temperature, with high insect numbers noted above 15°C (Lindblad & Arenö 2002). When the crop is not infected in the autumn, the damage from WDV will be very limited. Wheat shows mature plant resistance against WDV with resistance becoming evident at growth stage DC31, when the first node is detectable (Lindblad and Sigvald 2004). Therefore, when the winged adult form of *P. alienus* is ready to transmit WDV between wheat fields, the wheat has already reached the resistant stage. In continental and southern Europe, winter barley is affected by the barley strain of WDV. This strain is distinct from the wheat strain infecting wheat in Sweden and other parts of Europe and Asia (Ramsell et al. 2009). There is now a risk that the barley strain of WDV may appear also in Sweden. Similar problems with autumn infection of winter crops are expected with *Barley yellow dwarf virus*-PAV (BYDV-PAV) and BYDV-MAV, which are persistently transmitted by different aphid species. With increased temperatures in temperate regions, disease epidemics caused by aphid-borne viruses are likely to be more severe (Jones 2009). In Germany, a clear relation was recently found between the number of infection days in autumn and BYDV-attack in winter barley fields (Habekuß et al. 2009).

Interaction between abiotic and biotic constraints

It must be pointed out that dissecting the direct effects of climate change, a phenomenon with high complexity, is very intricate. We are presently learning from experiments carried out in controlled environments, what to expect from conditions with elevated CO_2 and ozone levels, in combination with higher temperatures. A Danish study has recently shown that single abiotic stress factors can impact fungal diseases differently compared to when they are combined (Lind Mikkelsen et al. 2010). For example, higher temperatures and increased ozone levels compromised basal resistance to powdery mildew in barley. Similarly, elevated CO_2 levels resulted in less foliar spot blotch (*Bipolaris sorokiniana*) whereas a combination of both higher temperatures and ozone concentrations instead led to increased colonization by the causal pathogen. This type of data clearly shows the high degree of complexity in plant-pathogen systems, and the impact of interactions between abiotic and biotic factors. Thus, breeding programmes to combat future disease problems need to be multi-factorial in these matters to become successful.

New opportunities

The rural landscape will slowly change with increased area of winter crops and more perennial crop species. Maize, a new crop in Sweden, is already expanding in area and is expected to become a major crop mainly for silage (Fågelfors et al. 2009). Whether grain maize will become adapted for Swedish conditions is unclear. Any introduction of genetically modified (GM) genotypes e.g. maize harbouring stem borer resistance is linked to heavy negative acceptance. To break the European stigma associated with GM biotechnology is a topic not elaborated on here. However, to replace the present heavy burden of chemical inputs on potatoes against late blight with a GM variety where the need of chemicals is reduced or eliminated may be one way to gain acceptance of this technology in our society (Park et al. 2009). There will be opportunities to grow many new crops in Sweden, not least on the horticultural side. It is envisaged that locally produced vegetables, fruits and other farm products will take major shares of the food market. Already today, a few farmers have started to grow grapes and fruit-trees like peaches to create new niches and income sources. The complex nature of the changes that are taking place provide an unprecedented challenge to adapting diversified agricultural production in Sweden, but at the same time there is a need to develop plant protection strategies to mitigate the negative effects of global warming.

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