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Climate change and potential future risks through wheat diseases: a review

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Abstract This review summarizes the most significant results from the so far existing, but fragmented studies on the potential effects of climate change on wheat pathogens and the diseases they cause. The analysis demonstrates that predictions are uncertain and future disease risk trends must be differentiated on a geographic and time scale. For example, disease incidence of Fusarium head blight in the United Kingdom might increase middle of this century, whereas disease severity of Septoria tritici blotch might decrease in France end of this century. Thus, wheat disease problems caused by a changing climate will probably not consistently worsen, as climatic changes may also improve the crop health situation in wheat depending on the location. The results of long-term simulations of future disease risk must be taken with caution, because different climate models and downscaling methods are used to make the projections and this can create considerable uncertainty. Being aware of this short-coming, plant pathologists recently started to assess the sources of uncertainty related to their long-term disease simulations. However, in spite of this progress there is still a significant lack of simulation studies related to different wheat diseases in various locations that could help to estimate future wheat grain losses due to climatic changes. Many more of these studies are certainly needed. Otherwise, the focus in the climate change debate will remain on the yield loss/gain potential due to changes in the environmental conditions only, which would neglect the important impact of altered biotic constraints such as diseases which are among the key factors in the estimation of future global wheat productivity.

Keywords *Triticum aestivum* · Fungal pathogen · Temperature · Global warming · Water/humidity · Disease simulation/forecast

Introduction

The objective of this review is to summarize (see below Tables 1 and 2) and validate the fragmented information on climate change and wheat diseases. The global human population is likely to increase to about nine billion in 2050 (United Nations 2011). In view of this projected population growth, climate sensitivity of global plant production may pose an additional threat to global food production and food security, particularly if unfavourable temperature and precipitation regimes, and increases in the frequency of extreme events such as hot spells, droughts, floods and storms would occur (Rosenzweig et al. 2001). In terms of harvested area, wheat (mainly common/soft wheat *Triticum aestivum,* but also durum/hard wheat *T. turgidum*) is the largest crop worldwide (about 217 million hectares in 2010; FAO 2012) and ranks third in the global annual production of commodities (about 651 million tons in 2010; FAO 2012). It is likely that climatic and atmospheric changes have an impact on wheat yield and quality (Ortiz et al. 2008; Bender and

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Table 1 Examples of anticipated effects of climate change on wheat pathogens/diseases. Most examples refer to winter wheat. Note: the simulation studies mentioned in this Table are summarized more in depth in Table 2

Geographic scope	Method of projection	Time horizon of projection compared to a baseline period in the 20th century	Anticipated effect of climate change on pathogen/disease	References (chronological order within each pathogen species)
Gaeumannomyces graminis (take all)				
Canada (Ontario)	Speculation[a]	Presumably[c] 2100	Decrease[d]	Boland et al. 2004
United Kingdom	Speculation	2020s and 2080s	Uncertain	Chancellor and Kubiriba 2006
United Kingdom	Speculation	Presumably 2050	Varied/unknown response	West et al. 2012a
Oculimacula yallundae (eyespot)				
Germany	Speculation	Presumably 2030	Decrease	von Tiedemann 1996
United Kingdom	Speculation	2020s and 2080s	Uncertain	Chancellor and Kubiriba 2006
Germany (North Rhine Westphalia)	Simulation[b]	2001–2050	Unchanged in all six sites investigated	Volk et al. 2010
Finland	Speculation	2025s, 2055s, and 2085s	Increase	Hakala et al. 2011
United Kingdom	Speculation	Presumably 2050	Increase	West et al. 2012a
Blumeria graminis (powdery mildew)				
Germany	Speculation	Presumably 2030	Decrease	von Tiedemann 1996
United Kingdom	Speculation	2020s and 2080s	Increase (2020), than decrease (2080)	Chancellor and Kubiriba 2006
Germany (North Rhine Westphalia)	Simulation	2001–2050	Increase in five out of six sites	Volk et al. 2010
Germany (Lower Saxony)	Simulation	2021–2050, 2071–2100	Decrease across Lower Saxony	Racca et al. 2012
Finland	Speculation	2025s, 2055s, and 2085s	Increase	Hakala et al. 2011
Sweden	Speculation	Presumably 2100	Increase, especially in winter cereals	Roos et al. 2011
United Kingdom	Speculation	Presumably 2050	Sporadic- capacity for more severe and less severe seasons	West et al. 2012a
Puccinia recondita (leaf rust)				
Germany	Speculation	Presumably 2030	Increase	von Tiedemann 1996
Canada (Ontario)	Speculation	Presumably 2100	Decrease	Boland et al. 2004
United Kingdom	Speculation	2020s and 2080s	Uncertain	Chancellor and Kubiriba 2006
France	Simulation	2020–2049, 2070–2099	Decrease	Gouache et al. 2011
Germany (North Rhine Westphalia)	Simulation	2001–2050	Increase in all six sites	Volk et al. 2010
Germany (Lower Saxony)	Simulation	2021–2050 and 2071–2100	Increase across Lower Saxony	Racca et al. 2012
United Kingdom	Speculation	Presumably 2050	Sporadic- capacity for more severe and less severe seasons	West et al. 2012a
Puccinia striiformis (stripe rust)				
Germany	Speculation	Presumably 2030	Decrease	von Tiedemann 1996
United Kingdom	Speculation	2020s and 2080s	Decrease	Chancellor and Kubiriba 2006
Germany (North Rhine Westphalia)	Simulation	2001–2050	Increase in four out of six sites	Volk et al. 2010
United Kingdom	Speculation	Presumably 2050	Sporadic- capacity for more severe and less severe seasons	West et al. 2012a
Puccinia graminis (stem rust)				
Canada (Ontario)	Speculation	Presumably 2100	Decrease	Boland et al. 2004
United Kingdom	Speculation	Presumably 2050	Sporadic- capacity for more severe and less severe seasons	West et al. 2012a

Table 1 (continued)

Geographic scope	Method of projection	Time horizon of projection compared to a baseline period in the 20th century	Anticipated effect of climate change on pathogen/disease	References (chronological order within each pathogen species)
Cochliobolus sativus (spot blotch)				
South Asia	Speculation	Not specified	Increase	Sharma et al. 2007
United Kingdom	Speculation	Presumably 2050	Increase	West et al. 2012a
Mycosphaerella graminicola (Septoria tritici leaf blotch)				
Germany	Speculation	Presumably 2030	Increase	von Tiedemann 1996
Canada (Ontario)	Speculation	Presumably 2100	Decrease	Boland et al. 2004
United Kingdom	Speculation	2020s and 2080s	Decrease	Chancellor and Kubiriba 2006
Germany (North Rhine Westphalia)	Simulation	2001–2050	Increase in all six sites	Volk et al. 2010
France	Simulation	2071–2099	Decrease	Gouache et al. 2012
United Kingdom	Speculation	Presumably 2050	Little change	West et al. 2012a
Phaeosphaeria nodorum (Septoria nodorum blotch)				
Germany (North Rhine Westphalia)	Simulation	2001–2050	Unchanged in four out of six sites	Volk et al. 2010
United Kingdom	Speculation	Presumably 2050	Little change	West et al. 2012a
Pyrenophora tritici-repentis (tan spot)				
Germany	Speculation	Presumably 2030	Increase	von Tiedemann 1996
Canada (Ontario)	Speculation	Presumably 2100	Decrease	Boland et al. 2004
Germany (North Rhine Westfalia)	Simulation	2001–2050	Unchanged in all six sites	Volk et al. 2010
Germany (North Rhine Westphalia)	Simulation	2021–2050, 2071–2100	Increase across Lower Saxony	Racca et al. 2012
United Kingdom	Speculation	Presumably 2050	Little change	West et al. 2012a
Tilletia controversa (stinking bunt)				
Canada (Ontario)	Speculation	Presumably 2100	Increase	Boland et al. 2004
United Kingdom	Speculation	Presumably 2050	Little change	West et al. 2012a
Tilletia indica (Karnal bunt)				
Europe	Simulation	2050	Increased risk of establishment in Europe	Baker et al. 2000
United Kingdom	Speculation	Presumably 2050	Increased risk of establishment in Europe	West et al. 2012a
Ustilago tritici (loose smut)				
Canada (Ontario)	Speculation	Presumably 2100	Increase[e]	Boland et al. 2004
Fusarium species (Fusarium head/ear blight)				
Germany	Speculation	Presumably 2030	Increase	von Tiedemann 1996
Canada (Ontario)	Speculation	Presumably 2100	Decrease	Boland et al. 2004
South America	Simulation	2020s	Increased risk in two out of three locations	Fernandes et al. 2004
Germany (North Rhine Westphalia)	Simulation	2001–2050	Increase in five out of six sites	Volk et al. 2010
United Kingdom	Simulation	2020s and 2050s	Increase	Madgwick et al. 2011
Sweden	Speculation	Presumably 2100	Increase	Roos et al. 2011
United Kingdom	Speculation	Presumably 2050	Increase	West et al. 2012a
Barley yellow dwarf virus (insect vectored virus disease)				
Germany	Speculation	Presumably 2030	Increase	von Tiedemann 1996
United Kingdom	Speculation	2020s and 2080s	Uncertain, first increase (2020), than decrease (2080)	Chancellor and Kubiriba 2006

Table 1 (continued)

Geographic scope	Method of projection	Time horizon of projection compared to a baseline period in the 20th century	Anticipated effect of climate change on pathogen/disease	References (chronological order within each pathogen species)
United Kingdom	Speculation	Presumably 2050	Increase	West et al. 2012a
Wheat soilborne mosaic (soilborne virus diseases)				
United Kingdom	Speculation	Presumably 2050	Little change	West et al. 2012a

[a] Speculations (assumptions) based on expert knowledge which considers the epidemiology of plant pathogens and the diseases they are causing, mainly based on their specific temperature and humidity requirements. The advantage of this method is that the complete cycle of a disease can be considered. However, this method is regarded to be somehow subjective

[b] Simulation studies usually do not consider the complete disease cycle. On the other hand, simulation studies are regarded to be more objective. According to Shaw (2009) disease forecast models useful for long-term climatic projections should at least be able to make good short-term forecasting

[c] According to the introduction of the article (note: no specific time span was specifically mentioned that directly referred to the speculation)

[d] In this Table it is not distinguished if the decrease or increase is little or great, which was done in some of the references listed (e.g. Boland et al. 2004)

[e] According to text page 338

Weigel 2011). A recent analysis using newly developed empirical and statistical models by Lobell et al. (2011) suggested that past climate change between 1980 and 2008 might have already reduced the potential global wheat production by about 5.5 %. This decrease was largely driven by increased average annual temperature up to 1 °C in some important regions of wheat production. As a result, at a global scale, warming from 1980 to 2008 may have offset some of the wheat yield gains achieved from agro-technical progress and rising atmospheric carbon dioxide (CO_2) content (Lobell et al. 2011). Therefore, the potential impact of climatic changes on wheat production as a major food crop has become an important global issue.

Wheat production is particularly at risk by global warming in regions which are considered to be vulnerable to increasing air temperature and/or reduced precipitation such as those which are located in south Asia (Lobell et al. 2011). For example, a simulation study focusing on climatic conditions in north-western India revealed, that acute water shortage combined with heat stress will adversely affect wheat productivity even under the positive effect of elevated CO_2 ('CO_2 fertilizer effect') in the future (Lal et al. 1998). However, a changing climate may not only bear threats but also opportunities in wheat production, particularly in regions currently limited by low temperature (Fuhrer 2006). Therefore, climate change might also improve conditions for wheat production, especially if appropriate adaptation methods are available and applied in the future (Ewert 2012).

The likely effects of a changing climate on future wheat yield potential are complex and in general the interactions between abiotic factors such as temperature, humidity and CO_2 are poorly understood. In fact, there still exists a high uncertainty of how climatic and atmospheric changes might affect future productivity of wheat and other food crops (Gornall et al. 2010). In addition, interactions with biotic stress factors may result in negative or positive consequences for future crop productivity and food supply (Boonekamp 2012). However, yield limiting biotic factors such as diseases have been neglected in most recently reported studies (Gregory et al. 2009; White et al. 2011). In 221 publications dealing with potential effects of climate change on crop yield, only two considered interactions with biotic risk factors (White et al. 2011).

In general, the projection of future global, regional, and local wheat yield potential is dependent on the emission scenario(s), climate model(s), and wheat simulation model(s) used (Toure et al. 1995; Ceglar and Kajfez-Bogataj 2012), among many other factors such as the soil type considered in the model runs (Ewert et al. 1999). Besides these factors hampering accurate predictions, there is a significant additional

Table 2 Simulation studies where wheat disease models (in few cases also crop models) were linked to outputs from regionalised climatic scenarios derived from one or several global circulation model(s) (GCM)

Geographic scope	GCM(s) used	Time span(s)[a]	Wheat pathogen/disease and projection of change	Reference (chronological order)
South America	1 GCM (A2)[b]	2020s	In La Estanzuela (Uruguay) and Passo Fundo (Brazil) Fusarium head blight risk index was greater under the climate change scenario (probably due to more rainy days from September to November) compared to the baseline period, whereas in Pergaminio (Argentinia) Fusarium head blight risk index did not increase.	Fernandes et al. 2004
France	4 GCM (A1B)	2020–2049, 2070–2099	In general, stagnation or even a reduction of potential yield losses due to leaf rust projected (in average about 15 % reduction), except for two locations in mountainous sites (Clermont-Theix and Avignon) if an early wheat variety (cv. Soissons) would be grown.	Gouache et al. 2011
Germany (North-Rhine-Westphalia)	1 GCM (A1B)	2001–2050	In the province North-Rhine-Westphalia (NRW), the disease infection risk increased [powdery mildew[c], Septoria tritici blotch[c], stripe rust[c], leaf rust[c], Fusarium head blight[d]] or did not change [eyespot[e], tan spot[f], Septoria nodorum blotch[g]] compared to the baseline period. Especially, infection risk by Septoria tritici leaf blotch was projected to increase in all six sites which are situated in different representative wheat cultivation areas throughout North-Rhine-Westphalia, which were considered in the simulation study.	Volk et al. 2010
United Kingdom	1 GCM (A2 and B2)	2020s, 2050s	Anthesis (GS 65) of winter wheat is projected to be progressively earlier by about 7–8 days and 11–15 days across United Kingdom by 2020s and 2050s respectively. Fusarium head blight incidence during anthesis is projected to increase, especially in southern England by the 2050s from currently 6–8 to 10–16% infested wheat plants (because of projected increase of temperature, while water availability for infection remains sufficient). Higher risks of grain yield losses and mycotoxin contamination of grain are the likely consequences.	Madgwick et al. 2011
France	4 GCM (A1B)	2071–2099	Depending on the sites (sites in three main wheat-growing areas were considered), average disease severity of Septoria tritici leaf blotch between the yield relevant growth stages GS 55 and GS 75 is projected to be reduced by 2–6 %. The occurrence of more low severity years and fewer high severity years are also projected. However, there is uncertainty associated with the projections ranging from 18 to 45 % (dependent on site), mainly due to the variability between global climate models and downscaling methods that were used. Results suggest that the fungicide use to control this disease could be reduced in the future.	Gouache et al. 2012
Germany (Lower Saxony)	1 GCM (A1B)	2021–2050, 2071–2100	In Lower Saxony the average infection risk of winter wheat between the crop growth stages GS 30 to GS 69 is projected to slightly decrease for powdery mildew and to increase for leaf rust and tan spot. As a likely consequence, target specific fungicide treatments might be adjusted correspondingly in the future.	Racca et al. 2012

[a] The respective time span(s) is/are compared to a baseline (e.g. 1961–1990, 1971–2000)

[b] In brackets: respective emission scenario(s) that were used

[c] Infection risk during winter-time (01 November–31 March) simulated in order to estimate inoculum pressure beginning of the growing season

[d] Infection risk simulated (01–15 June)

[e] Infection risk during winter-time and early spring-time (01 November–30 April) simulated

[f] Infection risk during spring-time (15 March–15 June) simulated

[g] Infection risk during spring-time (01 April–15 May) simulated in order to estimate inoculum pressure

risk that future wheat grain yield potential might be over- or underestimated if the significant modulating effects from biotic constraints such as diseases are ignored (Gregory et al. 2009), particularly, when considering the extremely high climate sensitivity of pathogens. The worldwide potential yield losses (without crop protection) and actual yield losses (with crop protection) of six globally important arable crops including wheat have been estimated (Oerke 2006). In spite of crop protection practices applied, actual grain yield losses in wheat in 2001–2003 were considerable. About 10 % of estimated actual yield losses were due to pathogens (fungi and bacteria) and 2 % to viruses (Oerke 2006). The question whether these estimated overall yield losses will be higher or lower under a globally changing climate will depend on the direct effects on pathogens and the indirect effects mediated through the host plant and adaptive management measures which will affect, for example, the predisposition of wheat for disease damage.

The aim of this review is to summarize and validate the fragmented information on potential climate change effects on wheat pathogens and the respective diseases, considering speculations based on expert knowledge and modelling studies of potential future wheat disease risks. The focus is on fungal pathogens, because they cause the major component of yield losses in wheat at the global scale, whereas viral and bacterial diseases are usually less important (Oerke 2006). In addition, the literature on viral and particularly bacterial wheat diseases with respect to climate change is extremely limited (Juroszek and von Tiedemann 2011; 2012). In this review information on the two major climate factors, temperature and humidity is compiled (note: complementary information on these two climate factors are contained in some previous review articles such as Coakley et al. 1999; Garrett et al. 2006, and Sutherst et al. 2011), whereas atmospheric factors such as CO_2 and ozone (O_3) are not considered. Information on the likely effects of elevated CO_2 and O_3 on plant-pathogen interactions can be found in previous review articles (Manning and von Tiedemann 1995; Eastburn et al. 2011; Pangga et al. 2011). The main conclusion of these reviews was that pathogens are rarely directly affected by elevated CO_2 and O_3, but these are more often indirectly affected through host plant responses to elevated CO_2 and O_3. This is one reason why atmospheric factors are in general not considered herein. The following section focuses on economically important wheat diseases. It presents a summary on speculations (simulation studies included) as to how the future importance of fungal wheat diseases might change under projected climate change in different countries (see Table 1). It is concluded that on a global scale, a particular wheat disease might not increase its future biological and economical importance consistently. Finally, in the last section the simulation studies of the future importance of fungal wheat diseases under projected climate change are discussed in more detail, such as the aspect how the material and methods used by different researchers might influence the long-term disease risk modelling studies (see Table 2).

Climate change and the likely future importance of fungal wheat diseases

The following fungal pathogens are major biotic constraints in intensive wheat production systems worldwide and will be considered in this paper. First, there are the obligate fungal pathogens (biotrophs), *Blumeria graminis* causing powdery mildew, *Puccinia graminis* causing stem rust, *Puccinia recondita* causing leaf rust, and *Puccinia striiformis* causing stripe rust. Second, there are crop residue-borne necrotrophic pathogens *Pyrenophora tritici-repentis* causing tan spot, *Mycosphaerella graminicola* causing Septoria tritici leaf blotch, *Phaeosphaeria nodorum* causing Septoria nodorum blotch, *Cochliobolus sativus* causing spot blotch, and *Giberella zeae*/anamorph: *Fusarium graminearum* and other *Fusarium* species causing Fusarium head or ear blight. There are many more fungal pathogens which are causing wheat diseases such as soil-borne root rots (Duveiller et al. 2007), a few of which are listed in Table 1. In regions with low productivity, and without seed dressing, smuts (e.g. common bunt caused by *Tilletia caries*) and bunts (e.g. Karnal bunt caused by *Tilletia indica*) can be of great importance (Oerke 2006). A comprehensive summary of wheat pathogens including fungi, viruses, and bacteria (and economically important animal pests) is provided in Bockus et al. (2010).

At a given location, a shift in warming and other climatic conditions such as altered precipitation may result in various changes of wheat diseases including: (1) the seasonal phenology (e.g. synchronization of pathogen life-cycle stages with their host plants and natural competitors or synergists), (2) the population dynamics (e.g. over-wintering and survival, changes in the number of generations of polycyclic pathogens), and (3) the geographic distribution (e.g. range expansion or retreat, and increased risk of pathogen invasion) (e.g. Chakraborty et al. 2000; Melloy et al. 2010; Sutherst et al. 2011; Ghini et al. 2012; Pangga et al. 2012; Pautasso et al. 2012; Siebold and von Tiedemann 2012a; West et al. 2012a; b).

The available knowledge on climate change and wheat diseases has not yet been comprehensively compiled. A few recent publications have included just a short paragraph, a more or less comprehensive case study, and/or a summary table of potential responses of wheat diseases to climate change (von Tiedemann 1996; Chakraborty et al. 1998; Baker et al. 2000; Boland et al. 2004; Chancellor and Kubiriba 2006; Chakraborty et al. 2008; Shaw et al. 2008; Legreve and Duveiller 2010; Paterson and Lima 2010; Volk et al. 2010; Chakraborty and Newton 2011; Fitt et al. 2011; Garrett et al. 2011; Hakala et al. 2011; Luck et al. 2011; Magan et al. 2011; Roos et al. 2011; Savary et al. 2011; West et al. 2012a; b). Moreover, there is an increasing number of articles which focus on particular wheat diseases in relation to climate change, e.g. on future changes of Fusarium foot rot in the United Kingdom (Pettitt and Parry 1996), future Fusarium head blight risk in South America (Fernandes et al. 2004) or in different European countries (Madgwick et al. 2011; West et al. 2012b; van der Fels-Klerx et al. 2012), future karnal bunt risk in Europe (Dumalasova and Bartos 2009), future worldwide changes in rust diseases (Chakraborty et al. 2011), future Septoria tritici leaf blotch risk in France (Gouache et al. 2012), and future changes of different wheat diseases in Punjab, India (Kaur et al. 2008). For example, the importance of stripe rust and Karnal bunt in Punjab, India is assumed to be reduced in the future due to temperature and humidity changes. On the other hand, the importance of leaf rust, foliar blights, Fusarium head blight, and stem rust may increase in Punjab in the future, the latter disease particularly in the absence of resistance in wheat cultivars (Kaur et al. 2008). This is in agreement with reports suggesting that climate change may modify the range of prevalent wheat diseases in some regions, with the result that currently economically less important pathogens may turn into potential threats in the future (Duveiller et al. 2007). Shifts within closely related species are also expected such as shifts in the composition of *Fusarium* species on cereal grain in Northern Europe (Parikka et al. 2012).

The above-mentioned scattered information on climate change effects on specific wheat diseases is systematically compiled in Table 1. It is obvious that the expected future importance of a specific wheat disease is not in agreement across the references listed. For example, the likely effect of climatic change on leaf rust varies from an increase to a decrease in future importance. There are several reasons for this variability. First, the geographic scope is different (Table 1). For example, expected effects in Germany may be different from those in France, because the prevailing climatic conditions are different in the two countries. Second, different methods were used in the studies, some relying on speculations and assumptions based on expert knowledge, others performing simulations using modelling approaches (Table 1). Speculations and assumptions based on expert knowledge usually allow consideration of the complete disease cycle, whereas simulation studies are usually restricted to one or a few stages of the complete disease cycle only. For example, Boland et al. (2004) considered three important disease cycle stages (the primary inoculum or disease establishment, rate of the disease progress, and potential duration of the epidemic) in their speculations and estimated a net effect on disease, whereas simulation studies may only consider the infection risk during a certain critical period of time (e.g. during winter-time where the accumulation of primary inoculum takes place in some diseases) in order to estimate inoculum pressure at the beginning of the growing season (e.g. Volk et al. 2010) or crop growth (Racca et al. 2012). The comparison of results therefore is difficult across the different approaches used in climate change research. Third, the future time span considered differs among authors (Table 1) and therefore the projected effect might be different as well, because the incidence and severity of a specific disease may change within this century. For example, the speculations by von Tiedemann (1996) are related to the period until 2030, whereas other researchers are targeting 2050 or 2100 in their projections. However, it might be that the importance of a specific disease will change differently from 2030 to 2050 compared to 2100. For example, Chancellor and Kubiriba (2006) assumed that the importance of powdery mildew in wheat in the United Kingdom will increase until 2020 and then will decrease until 2080 (Table 1). Fourth, even when comparing results of modelling approaches only, there might be great differences depending on the climate models used to make the projections such as reported recently by Gouache et al. (2012). More importantly, the variability of projections listed in Table 1 indicates that disease problems caused by a changing climate will probably not worsen consistently, but may also improve the crop health situation in wheat. Thus, on a global and/or national scale, a particular wheat disease might not increase its future biological and economical importance consistently.

In a study by West et al. (2012a), plant diseases were assigned to seven different ecotypes by considering fundamental similarities of the respective pathogens (mono- or polycyclic, strategy of spread, conditions required for infection, etc.). The goal was to estimate ecotype-related future disease response patterns to climate change in the United Kingdom, rather than validating single disease responses. Interestingly, most of the wheat diseases considered were predicted to have only little potential for change under the expected future climate in North-western Europe (Table 1). With few exceptions, little change is projected for the winter to spring foliar-infecting polycyclic rain-splashed fungi such as *M. graminicola* and *P. tritici-repentis*, because drier conditions at the end of the growing season may reduce disease severity on the upper leaves, although the same two diseases may be promoted during the early vegetative growth of wheat. This is in agreement with Boland et al. (2004) under conditions in Ontario, Canada (Table 1). The projected milder winters in Ontario may promote increased survival of most pathogens, for example, due to a reduced number of frost days. However, projected warmer and drier summers may hinder most fungal diseases (especially polycyclic diseases) and finally slow down or completely inhibit sporulation and disease progress. This might also result in reduced inoculum for the next season. However, in general it is difficult to determine which of the two contrasting factors (mild and wet winters vs. warm and dry late spring and early summers) outweighs the other (West et al. 2012a).

In addition, the possible advancement of the phenological growth stages of wheat due to increased temperature must be taken into account, which could partially compensate for effects of warming by repositioning key phases of wheat development such as flowering in earlier and therefore slightly cooler periods of the year (Gouache et al. 2011). For example, increased mean air temperatures of about 0.5–1.0 °C during the past few decades in Germany have led to the enhanced earliness of stem elongation and flowering of field crops such as wheat (Chmielewski et al. 2004). On the other hand, warmer winters in a temperate climate may promote and prolong crop growth during the vegetative period and interactions of temperature with photoperiod and vernalization may affect development of winter wheat, subsequently affecting the heading date (Miglietta et al. 1995). In addition, supra-optimal temperature conditions (>34 °C) can reduce the grain filling period of wheat mainly due to accelerated plant senescence (Asseng et al. 2011). Increased leaf senescence also has a strong impact on pathogens, particularly on those which depend on juvenile wheat leaves, namely biotrophic fungi such as *B. graminis* and *Puccinia* species. However, heat of more than 34 °C will also directly inhibit pathogen development and related diseases, because most fungal pathogens are suffering under extended periods of supra-optimal temperatures including most biotrophic fungi. In these cases it is difficult to distinguish if high temperature has directly affected pathogen development and the related disease or if the effect was mainly indirectly mediated through the host plant. This is a drastic example, but there may also be cases were the interaction between direct and indirect effects on pathogens and the respective diseases are more subtle. The same is true for interactions between temperature, humidity and any other abiotic factor such as wind and light which may have the capacity to influence pathogens directly or indirectly. Those additional factors may significantly modulate climate change effects as well, which should be kept in mind when focussing on effects of temperature and humidity on plant pathogens.

The timing of heading and flowering can also be manipulated by using cultivars with different ripening patterns (early vs. late) or by shifting the sowing date. All these management factors that could result in alternations of heading and flowering dates will likely have consequences for disease patterns in wheat, particularly for flower-infecting fungi such as *Fusarium* species and the threat imposed by mycotoxins in the harvested grain (West et al. 2012b). In addition to manipulating the heading and flowering dates of wheat through cultivar and sowing date choice, one major strategy in the context of climate change is conservation agriculture, because it enhances crop resilience in stressed environments (Ortiz et al. 2008). In countries, where cropping systems might be changing substantially due to warming, the pathogen distribution and prevalence might be more influenced by these changes which in turn increase the requirement of adaptation measures compared to countries where the current cropping systems will remain similar in the future. For example, in Finland, there are considerable future changes in arable farming practises possible. According to Hakala et al. (2011) two scenarios are likely to occur in the future: (1) an increased production of overwintering crops (winter wheat instead of spring wheat), and (2) the introduction of thermophilic crops such as maize (*Zea mays*), which currently cannot be successfully grown in Finland. This might mean that there will be a likely change from early summer to autumn pesticide use in wheat, which is likely to affect the prevalence of wheat pathogens in this country. The risk of mycotoxin contamination in wheat grain might become higher in the future (Hakala et al. 2011), because maize might be grown in a future warmer climate in Finland more frequently, enhancing the risk of Fusarium head blight and of mycotoxin contamination in the subsequent wheat crop (West et al. 2012b). Such risk is particularly high if sensitive wheat cultivars are grown and reduced soil tillage methods are applied prior to wheat sowing. Therefore, improved root health and durable resistance to the economically important pathogens is needed such as reported by Ortiz et al. (2008). The Finish example might be also of relevance to other countries or regions of the northern hemisphere with a similar agroecological environment, and where major changes in the wheat production system could be introduced.

Finally, there are some fungal pathogens that clearly thrive in warmer and drier conditions, such as *Ustilago* species and these might be increased in their significance as anticipated for Ontario under projected climate change (Boland et al. 2004). In addition, pathogens may also adapt to warmer conditions (Chakraborty et al. 2011). There is evidence for increased aggressiveness at higher temperatures of stripe rust isolates (*P. striiformis*) demonstrating that rust fungi can adapt to and benefit from higher temperatures (Mboup et al. 2012) to cause enhanced disease compared to previously less favourable environmental conditions (Milus et al. 2009). Therefore, more realistic disease simulation models should take into account known degrees of phenotypic plasticity and rates of microevolution, at least where possible (Garrett et al. 2012). One possibility to achieve this goal might be a continuous update of short-term disease forecasting models as a basis of long-term disease simulations in order to acknowledge the capacity of pathogens to adapt to environmental conditions such as temperature. To be able to identify these evolutionary processes of pathogen populations and to update short-term disease forecasting models with this information, long-term data sets from field observations are required. They will also help discriminating population shifts due to ecotypes adapted to changed climate from pathogen alterations driven by agronomical changes in the cropping systems (Scherm and Coakley 2003). In summary, the information gained with long-term data sets may help to improve the accuracy of modelling approaches significantly (Jeger and Pautasso 2008).

Wheat diseases considered in modelling approaches

Combining of data series and simulation models can be a valuable approach in projecting the future climate change impact on wheat diseases. It is particularly important to collect long-term data sets for weather parameters, crop development, and disease distribution and prevalence to be able to develop and validate linked 'climate-crop-disease' models (Butterworth et al. 2010; Evans et al. 2010; Madgwick et al. 2011; Richerzhagen et al. 2011).

In the past 10 years several such simulation studies (Fernandes et al. 2004; Gouache et al. 2011; Volk et al. 2010; Madgwick et al. 2011; Gouache et al. 2012; Racca et al. 2012) have attempted to link wheat disease forecasting models, a few also including crop models, to regional climatic scenarios derived from global circulation models (GCMs). These simulation studies considered parameters such as changes in timing of wheat anthesis and corresponding levels of disease incidence or the number of years with low and high disease severity (Table 2). For example, Fusarium head blight incidence during wheat anthesis is projected to become more severe, especially in southern England, by the 2050s (e.g. from currently 6–8 to 10–16% infested wheat plants), because of the projected increase in temperature, while water availability for infection will remain sufficient (Madgwick et al. 2011, Table 2). Therefore, improved control of Fusarium head blight should have a high priority in the future in order to reduce mycotoxin contamination of grain and to ensure food security

(Madgwick et al. 2011). In contrast, severity of Septoria tritici leaf blotch in France is projected to decrease by 2–6 % at the end of this century (Gouache et al. 2012, Table 2). Only one simulation study considered potential yield losses in addition to projections of disease severity parameters (Gouache et al. 2011). In this study, the effects of climate change on leaf rust were simulated and related to changes in grain yield of winter wheat in France (Gouache et al. 2011, Table 2). As a result, a stagnation or even reduction of wheat yield losses (in average about 15 % reduction) due to leaf rust has been projected for France (Gouache et al. 2011, Table 2), with the exception of two locations in mountainous sites. Here, an increase in yield losses is expected for an early cultivar, due to increased mean temperatures and an increased maximum severity of rust infection (Gouache et al. 2011). More of these long-term disease simulation studies that also include related yield changes for different pathogens and locations are necessary to quantify wheat grain yield losses or gains due to likely changes in future disease incidence and severity caused by climatic changes. Recently, Caubel et al. (2012) developed a conceptual design for modelling approaches that could be a useful tool to agronomists to integrate air-borne fungal pathogens and the diseases they cause in their crop models in order to estimate future crop productivity including disease impact. It is pointed out that agronomists and pathologists should work closely together to make progress in climate change research related to estimations of future global wheat productivity, allowing for the integration of abiotic and biotic factors in simulation studies on wheat productivity.

The comparison of model-based projections of the future prevalence and severity of diseases is hampered by the different underlying time periods where the projections are related to (Table 2, see also Table 1 and discussion above). In addition, different climate models, emission scenarios (Table 2) and downscaling methods have been used. Currently available climate models which are used in disease simulation studies are considered a major factor of uncertainty, among other factors, that contribute to the uncertainty of disease projections (Gouache et al. 2012). For example, the probability of an increasing average disease severity of Septoria tritici leaf blotch varied from 18 % to 45 % for three different locations in France (Gouache et al. 2012, Table 2). This study represents the first systematic quantification and analysis of different sources of uncertainty in the simulation of climate change impacts on a plant pathogen and its related disease. It appears to be a quite useful approach to validate how meaningful a projection is, and to improve the accuracy of future modelling, because both the source and degree of uncertainty can be estimated.

In general, future global temperature changes might be much larger than changes in precipitation, even when considering the most extreme precipitation scenarios (Lobell and Burke 2008). Therefore, it is suggested that future research should focus on the response of crops to temperature, e.g. by designing warming trials for major crops under representative field conditions (Lobell and Burke 2008; Siebold and von Tiedemann 2012b). These future experiments should include pesticide treated and untreated control plots, in order to differentiate the impact from abiotic and biotic factors on yield.

In conclusion, a lack of simulation studies has hampered until today the estimation of wheat yield losses as a result of climate change driven shifts in wheat diseases prevalence and severity. Therefore, many more quantitative data (Barnes et al. 2010) from simulation studies related to individual wheat diseases and locations are needed to integrate the yield loss potential of diseases in the climate change risk analysis. This will require an intensive collaboration between researchers from different disciplines involved in crop growth and disease epidemic modelling such as climatologists, agronomists, and plant pathologists. Most importantly, the focus in future climate change research must include biotic constraints such as fungal diseases in addition to the impact of abiotic factors on crop growth (e.g. temperature, precipitation, carbon dioxide, and ozone), in order to generate a more comprehensive and relevant projection of future global wheat productivity under a changing climate.

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