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Review

Climatic changes and the potential future importance of maize diseases: a short review

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Abstract

This mini-review summarizes the existing knowledge and hypotheses on the potential changes to the future importance of maize diseases due to projected global climatic changes. In contrast to fungal pathogens, there is almost no information available on viral and bacterial diseases. Most studies related to fungi refer to *Aspergillus* and *Fusarium* species, which are causal agents of maize ear rot, and the related risk of mycotoxin contamination of maize grain, potentially harmful to animals and humans. Just a single long-term simulation study based on a modelling approach driven by a climate change scenario has been reported for a maize disease so far. It projects a reduced risk of *Puccinia polysora* (southern rust) occurrence in Brazil in this century. More simulation studies, ideally those which also generate quantitative disease-yield loss data for different maize diseases and locations are certainly needed in order to include the future potential disease risk in maize to the climate change debate. This will enable the estimation of the future maize productivity based on both abiotic factors such as temperature and biotic factors such as diseases. A fundamental conclusion of this mini-review is that global maize disease problems caused by a changing climate will probably not consistently worsen, because climatic changes may also improve the crop health situation in maize depending on the disease, location and time scale considered, although ear rots and associated mycotoxin contamination of maize grain are expected to increase in many countries worldwide. Reducing ear rot disease risk is already of high priority and will likely demand particular attention in the future as well.

Key words: *Zea mays*, corn, fungal pathogen, temperature, global warming, speculation, simulation, forecast

Introduction

Maize (*Zea mays*) is the largest crop in terms of global annual production (about 844 million tonnes in 2010) and the second biggest crop related to the area harvested (about 162 million hectares in 2010) in the world (FAO 2012). It is hypothesized that climatic changes could directly affect maize yield and quality (Bender & Weigel 2011), due to a long-term trend towards higher temperatures, greater evapotranspiration, and an increase in the frequency of extreme weather events such as heat spells and temporary droughts, at least in some major maize production regions (Campos et al. 2004). An analysis by Lobell et al. (2011) suggested that the past climate change, especially between 1980 and 2008 may have reduced the potential global maize production by about 3.8% already, countervailing some of the yield gains from breeding and other technological advances (Lobell et al. 2011). If this trend continues, global food security might be threatened, particularly in view of the expected global human population increase from currently seven billion to about nine billion by 2050 (United Nations 2011), resulting in a considerable increase in the demand for maize grain in the future. In addition, the demand for maize for animal husbandry and bio-energy production will also increase. Therefore, pre- and postharvest maize biomass and grain losses must be minimized.

In many African countries, such as South Africa, maize production is especially put at risk due to greater heat and water stress (Dixon et al. 2003, Lobell et al. 2008). In Botswana yield of maize is projected to decline until mid century by about 10–36%, depending on region and soil type, mainly due to the projected shortened grain filling period caused by increased temperature and water stress in this country (Chipanshi et al. 2003). However, climate change might also provide opportunities for maize production, particularly in regions currently limited by low temperatures and where appropriate adaptation methods are being used in the future (Ewert 2012).

In addition to climatic and atmospheric factors, the future maize productivity will be dependent on climate change driven alterations in biotic stress factors such as diseases (Chakraborty et al. 2000). However, yield limiting biotic factors such as diseases have been neglected in yield simulation studies such as recently reported by White et al. (2011). Therefore, there is a risk that future maize grain yield potential might be over- or underestimated if future altered effects from biotic stress factors such as diseases are ignored (Boonekamp 2012).

In spite of current crop protection practices, 8.5% of the worldwide maize yield losses in 2001–2003 were estimated to be due to fungal and bacterial diseases (Oerke 2006), whereby the share of bacterial diseases is presumably very small. Losses varied greatly by region with estimated losses of about 4% in Western Europe and about 14% in West Africa and South Asia. In addition, there are worldwide losses in maize due to viral diseases, which were estimated to about 2.7% in 2001–2003. These also varied by region with estimated losses of about 2% in Western Europe and about 6% in West Africa (Oerke 2006). The loss potential (without plant protection) and the incurred actual losses (with plant protection) for maize diseases are almost similar (fungi and bacteria: 9.4 vs. 8.5%; viruses: 2.9 vs. 2.7%) (Oerke 2006), suggesting a lack of efficient control practices in this crop. However, global climatic and atmospheric changes may alter both the potential and actual yield losses of maize diseases.

According to the CIMMYT Maize Program (2004) economically important maize diseases in general include foliar diseases, smuts, stalk rots and ear rots (see below). The predominant maize diseases vary across environments. For example, in Asia banded leaf and sheath blight (caused by *Corticium sasakii*, anamorph *Rhizoctonia solani* f. sp. *sasakii*) is an emerging disease problem, whereas northern corn leaf blight caused by *Exserohilum turcicum* occurs worldwide (Cairns et al. 2012). Further diseases and pathogens with variable levels of importance in maize are shown below in Table 1.

The aim of this mini-review is to summarize the fragmented information on ‘climate change and maize diseases’. To the best of our knowledge, this is the first published summary on the potential future importance of maize pathogens and the diseases they cause. In this mini-review, we mainly focus on potential effects of temperature changes on pathogens, although the interactions with precipitation/humidity are also considered. Effects of atmospheric factors such as CO_2 and O_3 on plant-pathogen interactions have been reviewed previously (e.g. Manning & Tiedemann 1995, Eastburn et al. 2011, Pangga et al. 2013).

Climatic changes and potential effects on maize pathogens/diseases

General aspects

Climatic changes can indirectly and directly affect pathogens and the respective diseases, which has been recently reviewed in detail, for example, by Pautasso et al. (2012) and West et al. (2012). In addition, a comprehensive list of review articles published from 1988–2011 is provided in Juroszek & Tiedemann (2013a). Interested readers are referred to these publications for any details related to potential climate change effects on plant pathogens including maize diseases.

In short, indirect effects are (1) mediated through the host plant and/or (2) mediated through climate change driven crop management adaptations such as the introduction of irrigation, abolishment of deep soil tillage or shifted sowing dates. For example, the spread of irrigated maize in southeast Africa led to year-round cultivation and increased insect vector populations, culminating in increased *Maize streak virus* pressure in irrigated and also in rain-fed crops (Shaw & Osborne 2011). In principle, all important life cycle stages of fungal, bacterial and viral pathogens (survival, reproduction, and dispersal) are more or less directly influenced by temperature, humidity, light quality/quantity, and wind. Physiological processes of pathogens are particularly sensitive to temperature. This is also true for crops. Some ecological responses to recent climate change are already visible. For example, warmer mean air temperatures in Germany, especially in early spring since the end of the 1980s, have led to the advancement of phenological phases of field crops such as earlier beginning of stem elongation and flowering (Chmielewski et al. 2004). This can also affect crop pathogens (Siebold & Tiedemann 2013) including maize pathogens, particularly those which infect maize during flowering such as *Fusarium* species (Madgwick et al. 2011, Magan et al. 2011, Wu et al. 2011).

At a given location, a shift in warming and other climatic conditions such as altered precipitation may result in various changes in maize pathogens which in general include (1) geographical distribution (e.g. range expansion or retreat, and increased risk of pathogen invasion), (2) seasonal phenology (e.g. coincidence of pathogen lifecycle events with host plant stages and/or natural antagonists/synergists), and (3) population dynamics (e.g. over-wintering and survival, changes in the number of generations of polycyclic pathogens). This may finally result in altered disease incidence and severity (e.g. Coakley et al. 1999, Garrett et al. 2006, Tiedemann & Ulber 2008, Oldenburger et al. 2009, Chakraborty & Newton 2011, Richerzhagen et al. 2011, Sutherst et al. 2011, Ghini et al. 2012, Siebold & Tiedemann 2012a and 2012b, West et al. 2012). For example, warming may result in increased incidence of sorghum head smut in maize because of the causal agent *Sporisorium holci-sorghi* being likely favoured by hotter and drier conditions (as long as the upper temperature threshold of this pathogen is not exceeded), whereas *Kabatiella zeae* the causal agent of eye spot is likely to be disadvantaged by hotter and drier conditions. The result is that the regional distribution patterns of these diseases will be modified. On the other hand, pathogens also have the capacity to adapt to warmer conditions (Zhan & McDonald 2011, Mboup et al. 2012), and temperature/humidity dependent disease resistance of crop cultivars may be altered in the future (Huang et al. 2006, Juroszek & Tiedemann 2011). Most likely, plant pathogens will evolve and adapt to the new environmental conditions much faster than the crops including maize. Therefore, any speculations related to future disease risks in maize or other crops such as wheat (Juroszek & Tiedemann 2013b) should be made with considerable uncertainty.

Potential climate change effects on viruses and bacteria of maize

The potentially altered future importance of maize pathogens and diseases due to projected climatic changes in different continents and countries is compiled in Table 1. According to the CIMMYT Maize Program (2004), there are only few economically important bacterial diseases which are affecting maize. Just one speculation of the future importance of a bacterial maize disease has been reported so far in the literature (Table 1). In contrast, a large variety of viruses can cause maize diseases (CIMMYT Maize Program 2004). However, again just one speculation of the future importance of a viral maize disease has been reported so far (Table 1), although plant viruses and their vectors may be particularly favoured by high temperatures until the upper temperature threshold of the vectors and viruses is reached (Canto et al. 2009, Habekuß et al. 2009). In a 3-year field experiment in maize under tropical climatic conditions, Reynaud et al. (2009) showed that vector numbers of the leafhopper *Cicadulina mbila* and incidence of maize streak disease were closely associated with temperature, both increasing quickly above a threshold temperature of 24°C, whereas relationships with rainfall and relative humidity were less consistent, although both warm temperatures and high rainfall are considered to favour the vector and disease transmission (Chancellor & Kubiriba 2006). Therefore, global warming might promote many

Table 1: Examples of anticipated effects of climate change on the future importance of maize pathogens/diseases. Most examples refer to grain maize. Except Moraes et al. (2011) who used a modelling approach all other anticipated effects mentioned in this table are speculations[1)] based on expert knowledge. Except *Erwinia stewartii* and *Maize streak virus*, all other pathogens mentioned in this table are fungi.

Pathogen (disease)	Geographical scope	Time horizon of speculation[2]	Anticipated effect of climate change on the future importance[3]	References (chronological order within each pathogen species)
Pathogenic bacteria and viruses				
Erwinia stewartii (Stewart's disease, bacterium transmitted by insects)	Canada (Ontario)	Presumably 2100	Increase[5]	Boland et al. 2004
Maize streak virus, MSV (virus transmitted by leafhoppers, mainly *Cicadulina mbila*)	Sub-Saharan Africa	2020s and 2080s	Increase[10]	Chancellor & Kubiriba 2006
Pathogenic fungi				
Foliar diseases				
Kabatiella zeae (eyespot)	Canada (Ontario)	Presumably 2100	Decrease[4]	Boland et al. 2004
Cercospora zeae-maydis (grey leaf spot)	Canada (Ontario)	Presumably 2100	Increase[4]	Boland et al. 2004
Setosphaeria turcica anamorph *Exserohilum turcicum* (northern leaf blight)	Canada (Ontario)	Presumably 2100	Decrease[5]	Boland et al. 2004
	Sub-Saharan Africa	2020s and 2080s	Uncertain	Chancellor & Kubiriba 2006
Cochliobolus heterostrophus anamorph *Bipolaris maydis* syn. *Helminthosporium maydis* (southern leaf blight)	Sub-Saharan Africa	2020s and 2080s	Uncertain	Chancellor & Kubiriba 2006
Puccinia sorghi (common rust)	Canada (Ontario)	Presumably 2100	Decrease[6]	Boland et al. 2004
Puccinia polysora (southern rust)	Brazil	2020s, 2050s, 2080s	Decrease	Moraes et al. 2011
Smuts				
Sphacelotheca reiliana (head smut)	Germany	Presumably 2030	Increase	Tiedemann 1996
Sporisorium holci-sorghi (Sorghum head smut)	Sub-Saharan Africa	2020s and 2080s	Increase by 2080s	Chancellor & Kubiriba 2006
Ustilago maydis (common smut)	Canada (Ontario)	Presumably 2100	Increase[5]	Boland et al. 2004
	Sweden	Presumably 2100	Increase	Roos et al. 2011
Stalk rots				
Stenocarpella maydis syn. *Diplodia maydis* (Diplodia stalk rot)	Canada (Ontario)	Presumably 2100	Increase[6]	Boland et al. 2004
Fusarium and *Gibberella* species (*Fusarium* and *Gibberella* stalk rot)	Canada (Ontario)	Presumably 2100	Increase[6]	Boland et al. 2004
Pythium species (*Pythium* stalk rot)	Canada (Ontario)	Presumably 2100	Decrease[6]	Boland et al. 2004
Glomerella graminicola anamorph *Colletotrichum graminicola* (Anthracnose stalk rot)	Canada (Ontario)	Presumably 2100	Decrease[4]	Boland et al. 2004

Table 1: (Continued)

Pathogen (disease)	Geographical scope	Time horizon of speculation[2]	Anticipated effect of climate change on the future importance[3]	References (chronological order within each pathogen species)
Ear rots[7]				
Aspergillus flavus, A. parasiticus (aflatoxin producer)	Europe, USA	Future in general	Increase	Paterson & Lima 2010
	Australia	Future in general	Decrease	Paterson & Lima 2010
	Africa, Latin America, and Asia	Future in general	Increase[8]	Savary et al. 2011
	USA	Near- and long-term future	Increase	Wu et al. 2011
Fusarium species	Canada (Ontario)	Presumably 2100	Increase[5]	Boland et al. 2004
Fusarium graminearum (DON, ZEA producer)	Finland	2025s, 2055s, and 2085s	Increase[9]	Hakala et al. 2011
	Africa, Latin America, and Asia	Future in general	Decrease[8]	Savary et al. 2011
	USA	Near- and long-term future	Decrease, Increase[9]	Wu et al. 2011
	United Kingdom	Presumably 2050	Increase	West et al. 2012
Fusarium verticillioides (fumonisin producer)	Africa, Latin America, and Asia	Future in general	Increase[8]	Savary et al. 2011
	USA	Near- and long-term future	Increase	Wu et al. 2011

[1] Speculations (assumptions) based on expert knowledge which considers the epidemiology of plant pathogens and the diseases they cause, 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.

[2] Compared to a baseline period in the 20th century.

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

[4] Refers to grain maize only.

[5] Refers to grain maize and sweet corn.

[6] Refers to sweet corn only.

[7] Pathogens causing these diseases are responsible for mycotoxin contamination of maize grain both pre- and postharvest.

[8] In subtropical and tropical regions, where temperature, drought events, and insect injury (predisposition of plants to infection) will increase.

[9] In relatively cool areas where maize cultivation will be introduced and/or expanded due to climate change.

[10] In areas possible where rainfall is not limiting.

insect vectors and the virus diseases they transmit, at least within a certain temperature range, since the study by Reynaud et al. (2009) also showed that temperatures of 30°C and above might be detrimental for the virus vector *C. mbila* and related virus transmission. As speculations on climate change driven alterations of viral and bacterial maize diseases are extremely limited, the present mini-review focuses on fungal diseases.

Potential climate change effects on fungal leaf diseases of maize

In a publication, considering both grain maize and sweet corn under temperate climatic conditions in Ontario, Canada, Boland et al. (2004) speculated on the future importance of several maize diseases. The authors considered three important disease cycle stages (the primary inoculum or disease establishment, rate of disease progress, and potential duration of an epidemic) and estimated a net effect on the respective maize disease. They projected milder winters in Ontario may promote increased survival of most pathogens, 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 disease progress. This might also result in reduced inoculum for the next season. The authors concluded that one leaf disease is anticipated to increase, whereas three other leaf diseases are supposed to decrease in Ontario during this century due to projected climatic changes (Table 1). On the other hand, stalk rot diseases are anticipated to increase in Ontario (see below). Therefore, the total number of diseases may not change dramatically, but there might be some changes in the future range of maize diseases in Ontario. However, in general it is difficult to determine which of the two contrasting factors (mild and wet winter weather *vs.* warm and dry late spring and early summer weather) outweigh the other (West et al. 2012). Even when only a single factor such as temperature is considered and therefore interactions with other environmental parameters such as humidity are neglected, the response of a particular pathogen is difficult to determine because each life cycle stage of a pathogen might respond differently to warming (Goudriaan & Zadoks 1995). Considering these countervailing effects and other likely factors which might contribute to unpredictable interactions (see above), Chancellor & Kubiriba (2006) assumed that the future importance of northern and southern leaf blight is uncertain in areas like sub-Saharan-Africa (Table 1).

Potential climate change effects on smuts of maize

Interestingly, there is a general agreement that the future importance of smuts in maize may increase, independently on the geographical scope and time scale of the speculation (Table 1). In each case a different pathogen species (*Sporisorium holci-sorghi*, *Sphacelotheca reiliana* and *Ustilago maydis*) was considered in these speculations. Nevertheless, all pathogens do have in common that they cause smuts and that they thrive under warm and dry conditions such as optimal for *U. maydis* (Boland et al. 2004), as long as the upper temperature threshold of each pathogen is not exceeded.

Potential climate change effects on stalk rots of maize

Boland et al. (2004) also considered stalk rots of maize, particularly related to sweet corn under temperate climatic conditions in Ontario, Canada. The importance of Diplodia stalk rot and Fusarium/Gibberella stalk rots may increase in sweet corn, whereas the future importance of Pythium stalk rot might decrease. Anthracnose stalk rot in grain maize may also decrease (Table 1). Thus, some stalk rot causing pathogen species will be replaced by other stalk rot pathogen species, which are better adapted to the future temperature and moisture conditions in Ontario. Consequently, stalk rot diseases in maize will remain similarly important in the future in Ontario. No report exists on the future importance of stalk rot of maize in other countries. Therefore, the question remains if the Canadian example is also relevant to other countries or regions of the northern hemisphere with a similar agroecological environment, where grain maize and sweet corn are grown. This question, however, is not easy to answer and deserves careful considerations.

Potential climate change effects on ear rots and related mycotoxin contamination

A truly alarming issue is the potential risk deriving from ear rot diseases which may be expected to increase in a future climate change scenario in many areas of the world (Table 1). Alarming because ear rots are associated with increased mycotoxin contamination of maize with negative human and animal health consequences. One reason for the fact that most authors assumed an increased risk of ear rot diseases in the future might be that ear rot of maize can be caused by many different pathogens with partly different environmental requirements (for review see e.g. Paterson & Lima 2010, Magan et al. 2011, Wu et al. 2011). Hence, one ear rot causing pathogen species may be simply replaced by another, which is better adapted to the changed environment. Therefore, the competition among pathogen species that cause ear rot might be influenced by climatic changes with no obvious change of the overall disease symptoms, but with dramatic effects on human and animal health by shifting towards the prevalence of more harmful mycotoxins in maize grain. If in subtropical and tropical regions temperature, drought, and insect injury (predisposition of plants to infection) would increase, an increase of *Aspergillus flavus* (aflatoxin producer) and *Fusarium verticillioides* (fumonisin producer) may occur at the expense of *F. graminearum* (deoxynivalenol DON and zearalenone ZEA producer) (Table 1). Aflatoxins, produced by *A. flavus* and *A. parasiticus* are hepatocarcinogenic in humans, particularly in conjunction with chronic hepatitis B or C virus infection (Wild & Gong 2010). Fumonisins produced by *F. verticillioides* and *F. proliferatum* are classified as Group 2B ‘possibly carcinogenic to humans’ with a possible link to increased oesophageal cancer (Wild & Gong 2010). DON and ZEA are also harmful to human and animal health, but appear to be less acute toxic than aflatoxin and fumonisin (Murphy et al. 2006). DON can inhibit the protein synthesis and cause immune dysfunctions (Sudakin 2003), whereas ZEA and its metabolites possess oestrogenic activity among other harmful activities in humans and animals (Zinedine et al. 2007). A potential shift to *Aspergillus* species and *F. verticillioides* is definitely not desired with regard to human and animal health, although in the future methods to detoxify mycotoxins may be available (Karlovsky 2011). The potential risks related to altered mycotoxin contamination of maize grain are represented in detail in Table 1.

Lack of maize disease simulation studies driven by climate change scenarios

Only one long-term simulation study is currently available that projects an altered risk of a disease in maize based on a disease modelling approach which is linked to climate change scenarios from climate models (Moraes et al. 2011, Table 1). This simulation study suggests that the risk of occurrence of southern rust (*Puccinia polysora*) will decrease in most regions in Brazil this century because of an increase in mean air temperature. There is an urgent need to predict which maize diseases are likely to increase in importance but this requires coupled crop-disease-weather interaction models (West et al. 2012). It is important to base these long-term projections of plant disease on high quality long-term data sets of the crop, disease and historic weather, which will result in the development of reliable disease-yield loss models (West et al. 2012). Finally, these data must be linked to appropriate climate change scenarios (Evans et al. 2010, Madgwick et al. 2011). However, in general, these long-term data sets on crops and related disease incidence and severity are rare (Jeger & Pautasso 2008), particularly in maize, presumably because of a lack of foresight and the short-term nature of many research projects. In addition, in many countries maize crops are not treated with fungicides yet. Therefore, with few exceptions (e.g. Paul & Munkvold 2005) short-term disease forecasting systems which guide fungicide treatments in maize do not seem to be sufficiently developed as compared to wheat diseases (see review by De Wolf & Isard 2007). However, short-term disease forecasting models are usually needed to create long-term disease simulations driven by scenarios of climate models, although short-term disease forecasting models may not always be suitable for long-term disease simulations because they were not developed for this special purpose (Shaw & Osborne 2011, Garrett et al. 2012). To summarize, the so far limited significance of fungal diseases in maize in some regions (although in others quite significant, see Introduction) appears to be an important reason for the lack of long-term simulation studies of maize diseases which could be used in fungal disease risk projections based on expected climate change scenarios.

Conclusion

The present state of knowledge suggests that global losses of maize yield due to pathogens are lower compared to weeds and animal pests (Oerke 2006). In addition, yield losses in maize due to fungal pathogens are relatively lower compared to other crops such as potatoe (*Solanum tuberosum*) and wheat (*Triticum aestivum*) (Oerke 2006). These are two likely reasons why disease modelling approaches and assessment studies on climate change impacts related to maize diseases are scarce until today. In spite of the lower significance of most fungal diseases in maize compared to potatoe and wheat in many countries until today (e.g. Europe), it is even more important to obtain information on the potential long-term alterations of the importance of maize diseases driven by climatic changes in order to plan ahead for appropriate adaptation strategies.

Global maize disease problems caused by a changing climate will probably not consistently worsen, because climatic changes may also improve the crop health situation in maize depending on the environmental requirements of the disease, the present-day and future climatic conditions of the location and the time scale considered in the projections (see Table 1). Nonetheless, the importance of maize pathogens such as *Aspergillus flavus* and the related mycotoxin contamination of maize grain may increase under future warming in several continents such as highlighted in Table 1. This is alarming because ear rots are associated with increased mycotoxin contamination of maize with negative human and animal health consequences, although in the future methods to detoxify mycotoxins may be available (Karlovsky 2011).

According to Barnes et al. (2010) the need to adapt crop cultivation and crop protection to climatic changes may not be obvious to farmers at first glance, because the effect of disease on yield might be compensated by yield promoting factors such as improved cultivars or cultivation methods (Lobell et al. 2011). On the long-term, however, farmers will adapt their cropping practices including crop protection according to requirements imposed by environmental changes, as they have done with great success in the past.

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