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Effects of regional climate change on brown rust disease in winter wheat

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Abstract Projected climate changes will affect wheat crop production both in the main processes of plant growth and development but also in the occurrences and severities of plant diseases. We assessed the potential infection periods of wheat leaf rust (WLR) at two climatologically different sites in Luxembourg. A threshold-based model, taking hourly values of air temperatures, relative humidity and precipitation during night-time into account, was used for calculating favourable WLR infection days during three periods throughout the cropping season. Field experiments were conducted during the 2003–2013 period at the selected sites. Projected climate data, from a multi model ensemble of regional climate models (spatial resolution 25 km) as well as an additional projection with a higher spatial resolution of 1.3 km, were used for investigating the potential WLR infection periods for two future time spans. Results showed that the infections of WLR were satisfactorily simulated during the development of wheat at both sites for the 2003–2013 period. The probabilities of WLR detection were close to 1 and the critical success index ranged from 0.80 to 0.94 (perfect score = 1 for both). Moreover, the highest proportions of favourable days of WLR infection were simulated during spring and summer at both sites. Regional climate projections showed an increase in temperatures by 1.6 K for 2041–2050 and by 3.7 K for 2091–2100 compared to the reference period 1991–2000. Positive trends in favourable WLR infection conditions occur at both sites more conducive than in the reference period due to projected climatic conditions.

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1 Introduction

Plant diseases caused by fungi and fungi-like pathogens are recognized as posing major threats to cereals production worldwide. Fungal diseases affecting wheat production, such as wheat leaf rust (WLR, caused by *Puccinia triticina* Eriks) or stripe rust (caused by *P. striiformis* f. sp. *tritici*), have drawn more attention because of their increasing economic importance (El Jarroudi et al. 2009b; Hovmøller et al. 2008; Ordoñez and Kolmer 2007; Roelfs et al. 1992). Yield losses associated to wheat rusts reach up to 70 % in susceptible wheat cultivars, when the diseases are uncontrolled (Oerke and Dehne 1997; Roelfs et al. 1992). Both grain quantity and quality can be affected by severe infections. Although resistant wheat cultivars are grown as means to control the disease development and spread, the mutation of rust pathogens and the production of new races capable of attacking new cultivars are of major concern. An example of an emergent virulent race is the strain Ug99 (causing stripe rust), which is threatening 80 % to 90 % of current wheat cultivars (Hodson 2011; Pretorius et al. 2000; Singh et al. 2011). Studies on the distribution of WLR populations have revealed a diversity of virulence phenotypes according to the geographical regions, along with new phenotypes recorded (e.g. El Jarroudi et al. 2009b; Kolmer et al. 2011; Kosman et al. 2014; Ordoñez and Kolmer 2007).

The relationships between weather conditions and wheat rust diseases have been extensively studied (e.g. El Jarroudi et al. 2014a; Eversmeyer and Kramer 2000; Huerta-Espino et al. 2010). Important factors conducive to the infection and progress of WLR are relative humidity, air temperatures, and precipitation. Generally, optimum air temperatures for the germination of WLR urediniospores ranged from 12 °C to 15 °C, with the process stopping at temperatures >35 °C (De Vallavieille-Pope et al. 1995). Light intensity can delay or inhibit the infection (Eversmeyer and Kramer 2000). Furthermore, leaf wetness induced by air moisture is essential for the germination and the penetration of uredospores. In Luxembourg, El Jarroudi et al. (2014a, 2014b) have shown that the development of WLR requires a period of night weather conditions of at least 12 consecutive hours with air temperatures between 8 °C and 16 °C, relative humidity >60 %, and precipitation <1 mm.

With the worldwide expected changes in the climate during the coming decades (IPCC 2014), the patterns of fungal diseases will be affected accordingly (Barford 2013; Chen et al. 2011; Coakley et al. 1999; Fisher et al. 2012; Luck et al. 2011). Fungi-related emerging infectious diseases might be more recurrent, with potential negative implications for human and ecosystem health (Fisher et al. 2012). Trends in the polewards moves of crop pests and pathogens, already observed (Bebber et al. 2013; Chen et al. 2011) might sustain, though the changes in climate might improve the crop health situation in some regions, including wheat production zones (Juroszek and von Tiedemann 2013). The impacts of climate changes on crop yield and production at regional scale in Europe have been analysed by e.g. Moore and Lobell (2015) or Vanuytrecht et al. (2015). In Luxembourg, studies involving the cabbage stem weevils (*Ceutorhynchus pallidactylus*) and the rape stem weevil (*C. napi*) have shown potential changes in their migration into crops under future regional climatic conditions (Eickermann et al. 2014; Junk et al. 2012). Further, changes in the crop growing season will occur, with an elongation of the thermal vegetation period, mainly related to an earlier onset in spring (Goergen et al. 2013; Junk et al. 2012).

Although the potential first appearance and subsequent progress of fungal diseases is essential for planning optimal fungicide applications, until now only a few studies have been devoted of such assessments under projected future climate conditions. Helfer (2014) investigated the influence of global change on rust fungi and Mikkelsen et al. (2015) described the impact of increased CO_2 levels and projected changes in ozone concentrations and air temperature on fungal diseases in barley. Our study aimed therefore to fill the gap and to explore the potential effects of regional climate change effects on the different infection conditions of WLR in Luxembourg. Luxembourg was chosen as a study area because of the availability of extensive field observations. The methodology presented here can be readily transferred to other regions and other fungal diseases by adjusting the meteorological threshold values for the disease development.

2 Materials and methods

2.1 Study sites and disease monitoring

Two sites, located in different climatological regions of Luxembourg, were considered for this study: Burmerange (49°29’N, 6°19’E, 248 m AMSL) in the south and Reuler (50°03’N, 6°01’E, 452 m AMSL) in the north of the country. Field experiments were carried out during the 2003–2013 winter wheat cropping seasons. A description of the plot design as well management practices can be found in El Jarroudi et al. (2009a). Various wheat cultivars differing in rust susceptibility were distributed among sites during the study period. Details of the susceptibility of the wheat cultivars were shown in the online resource 1. Fields were sown in mid-October and the sowing and harvest methods as well as crop practices used, reflected the usual wheat production practices in Luxembourg. The monitoring of the disease levels were done by visual assessments of the WLR between the growth stage (GS) 31 and GS 85 (Zadoks et al. 1974) during the cropping season from mid-April to July of each year. The total leaf area covered by the disease symptom in percent was used as criteria. To ensure constant quality of the visual disease assessment field technicians were trained using the disease assessment software Distrain (Tomerlin and Howell 1988) and standard area diagrams for cereal diseases (James 1971). Each year ten plants were marked at the beginning of the growing season and the monitoring was done on a weekly basis throughout the growing season.

2.2 Regional climate change projections

Advances in the understanding of the physical processes of the climate system and the implementation of that knowledge in numerical models have increased the reliability of regional climate change projections in the last decades. To assess possible future climate conditions at the regional level of Luxembourg two data sets were used i) results from a combination of 15 different global circulation models (GCM) and regional circulation models (RCM) with a spatial resolution of 25.0 km of the ENSEMBLES project (daily data) and ii) a RCM model run with a convection permitting high spatial resolution of 1.3 km (hourly data).

To assess the continuous evolution of the climate conditions at Luxembourg, the 15 different transient GCM-RCM combinations of the EU ENSEMBLES project were used. They cover the period from 1961 until 2100 (van der Linden and Mitchell 2009). Time series of daily mean air temperature as well as precipitation totals were retrieved from the

ENSEMBLES data repository at the Danish Meteorological Institute (http://ensemblesrt3.dmi.dk, 2013–09-30). All model realisations were part of the same experimental design and used the A1B emission scenario (IPCC 2000). The different GCM/RCM combinations as well as the institutions that conducted the model runs were shown in the online resource 2.

For the assessment of the WLR disease risk in Luxembourg hourly data were necessary. To provide this data and also to assess spatial differences within the country, the non-hydrostatic limited-area atmospheric prediction model COSMO-CLM (version 4.8_clm11) of the consortium for small-scale modelling COSMO (Baldauf et al. 2011) was used. A three way nesting approach was applied where the global model ECHAM5 (forced with A1B scenario) has first been downscaled to 0.165° (18 km) in a domain covering continental Europe (Hollweg et al. 2008). After that the results have been dynamically downscaled to a resolution of 0.04° (4.5 km) in a domain covering part of Western Europe. The final target domain covers Luxembourg and the German states of Rhineland-Palatinate and Saarland, as well as parts of northern France and eastern Belgium with a spatial resolution of 0.0118° (1.3 km) (Gutjahr and Heinemann 2013). Due to computational constrains three time slices of ten years each (1991–2000, 2041–2050, 2091–2100) have been modelled instead of transient model runs. Hourly values of mean air temperatures, relative humidity and precipitation were extracted from the output files. In order to assess the spatial differences time series for two pseudo stations (Reuler and Burmerange), situated in climatologically characteristic regions for Luxembourg were extracted.

2.3 Assessing the potential infection periods of wheat leaf rust

For each year of the study periods (2003–2013, 1991–2000, 2041–2050, and 2091–2100), three different time spans were analysed; winter (21. Dec. to 21 March; N = 91), spring (22 March to 10 May; N = 50) and summer (11 May to 10 July; N = 61). The most critical period of potential harmful fungal diseases development to grain yield in wheat is the period spanning the development of the upper three leaves (L1-L3, L1 being the flag leaf). This period generally occurred during May to June. Nevertheless, weather conditions were also analysed for wintertime and springtime because favourable conditions to the presence of WLR spores during winter can lead to earlier infections at the resuming of wheat growth (i.e., overwintering), and earlier infections in springtime can foster the progress of the disease onto upper leaves later in the growing season.

The disease model for brown rust by El Jarroudi et al. (2014a, 2014b) was used to describe the infection and progress of WLR at the two test sites. Air temperature, relative humidity and precipitation were the main drivers for that disease. El Jarroudi et al. (2014a) have shown that the meteorological conditions during the night (8 p.m. until 5 a.m. included) are more important than daytime conditions for the disease progress. The following meteorological conditions are conducive for the development of WLR and were used as threshold values. At the beginning of the epidemic, hourly precipitation totals between 0.1 mm and <1 mm were required for spores deposit on leaves. After that initial precipitation event, 12 h of air temperature between 8 °C and 16 °C, relative humidity >60 % and precipitation <1 mm must be fulfilled in two consecutive nights.

For each year of the study cropping seasons potential infection periods of WLR were calculated according to these conditions. The evaluation of the capability of the disease model to correctly simulate the occurrence of WLR was based on contingency scores for the probability of detection (POD), false alarm ratio (FAR) and critical success index (CSI) of WLR infection. They were calculated as follows,

$$\mathrm{POD} = \mathrm{a} / (\mathrm{a} + \mathrm{c})$$
$$\mathrm{FAR} = \mathrm{b} / (\mathrm{a} + \mathrm{b})$$
$$\mathrm{CSI} = \mathrm{a}/(\mathrm{a} + \mathrm{b} + \mathrm{c})$$

where *a*, *b* and *c* refer to infections both observed and simulated, infections simulated but not observed, and infections observed but not simulated, respectively.

3 Results

3.1 Climate change signals for Luxembourg

Based on the ENSEMBLES results and the CLM projection the potential changes on air temperature and precipitation can be assessed for Luxembourg (Junk et al. 2014; Matzarakis et al. 2013; Molitor et al. 2014; Lokys et al. 2015). According to the suggestions of Ylhäisi et al. (2010) or Collins et al. (2013), no weighing scheme to the different model outputs of the ENSEMBLES data were applied. Figure 1 shows the air temperature anomalies (with reference to 1991–2000) for the period from 1971 to 2100. Due to the restricted availability of the COSMO-CLM data set, we used a shorter reference period of only 10 years (1991–2000) for this comparison. The results of the ENSEMBLES data sets are shown as multi-model bandwidth (grey shaded area in Fig. 1) and multi-model mean (blue line in Fig. 1). Included are also the ten year averages of the COSMO-CLM projection. The COSMO-CLM projections are within the spread of the ENSEMBLES data underlying the suitability of this data set for this impact study. Compared to the reference period air temperature increased by 1.6 K in the near (2041–2050), and by 3.7 K in the far future (2091–2100), based on the COSMO-CLM projections. The projected positive air temperature trends for the annual values were statistically significant (P = 0.05). The change signal for the annual precipitation values was less pronounced. A slight increase of 22 mm for the near and 16 mm for the far future was derived (data not shown here).

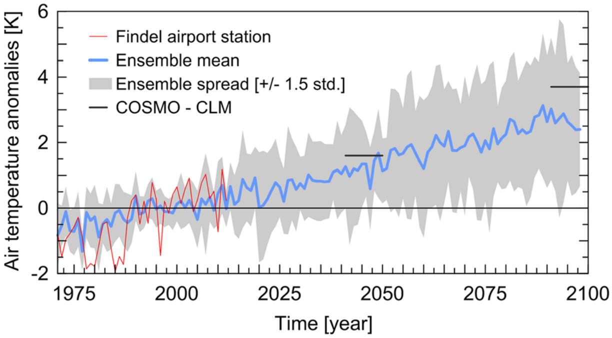

Fig. 1 Time series of annual mean air temperature anomalies over the 1971–2100 period compared to the reference period (1991–2000). Blue line: multi-model mean (N = 16 RCMs; 1961–2098) of the ENSEMBLES data set; grey shading: multi-model bandwidth (+/− 1 x standard deviation). Short black line: mean values of the two selected sites from the COSMO-CLM data set (2041–2050, 2091–2100). To relate these climate change projections for Luxembourg to local observations, data for the Findel airport station are additionally shown

3.2 Performance of the threshold-based model for wheat leaf rust infections

The threshold-based model has been successfully evaluated over the 2003–2009 cropping seasons (El Jarroudi et al. 2014a; El Jarroudi et al. 2014b). Overall, the FAR of leaf rust occurrences on upper leaves (L3-L1) ranged from 0.06 to 0.20 at both sites during 2003–2009 (best score = 0). The POD (probability to forecast correctly the observed event) was greater than 0.97, and the CSI (which takes into account both false alarms and missed events) ranged from 0.80 to 0.94 during the same period at the two sites (perfect score for POD and CSI = 1). Likewise, FAR, POD and CSI calculated for the same period (end of spring- beginning of summer times) over the 2010–2013 cropping seasons showed that the threshold-based model for WLR gave reliable information (POD >0.95, CSI ≥0.90). Furthermore, similar statistics for the WLR occurrence expressions on the lower leaves (L6-L4) were found during the 2003–2013 period. Note that lower leaves developed generally from the second half of spring time onwards.

3.3 Wheat leaf rust infection periods and disease severity based on observations

The proportions of favourable days for WLR infection throughout winter, spring and summer times over the 2003–2013 period are presented in Fig. 2a-b. Generally, highest values of favourable days occurred in spring and summer times at both sites. At Burmerange 6 years (2004, 2006, 2007, 2009, 2012 and 2013) out of 11 years had more than 30 % of infection days in summer (5 years in spring), with a peak of 59 % in 2007.

From those 6 years only 2006 and 2007 had no proportion of infection periods >30 % in spring. At Reuler high proportion of favourable days were mostly observed in summer time (4 years with favourable days >30 % with a peak of 52 % in 2009). The wintertime show lower favourable days to WLR infection (proportions ≤20 %) compared to the site of Burmerange, with two cropping seasons with no favourable days (2005 and 2006). The first dates of WLR

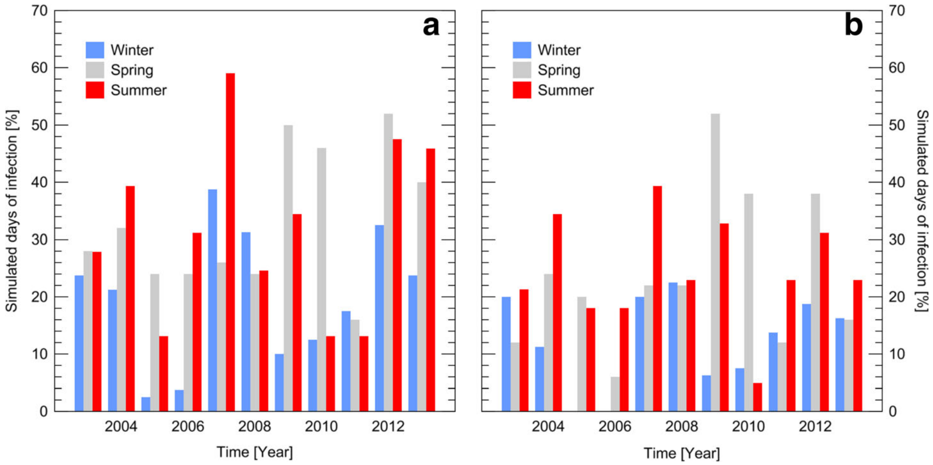

Fig. 2 Proportion of simulated days of wheat leaf rust (WLR) infections at a) Burmerange and b) Reuler throughout the winter, spring and summer times during the 2003–2013 period. Winter time was defined from 21 December to 21 March (N = 91), spring was from 22 March to 10 May (N = 50), and summer was from 11 May to 10 July (N = 61). Simulations were based on the threshold-based model for WLR as described in El Jarroudi et al. (2014a)

infections, as well as the date of maximum WLR severity, as recorded throughout the monitoring period over 2003–2013 are presented in Table 1. Infections appeared earlier at Burmerange over the years, compared to Reuler. The severity of WLR was higher at Burmerange than at Reuler. The average disease severity on the two upper leaves between GS 75 and GS 87 was up to 74 % (in 2003) at Burmerange. Whilst at Reuler, the severity did not exceed 4 % over the 11-year period of disease monitoring. Dates of maximum WLR severity at both sites were almost the same (or 1 week apart when different) over the monitoring period.

3.4 Combination of thresholds for wheat leaf rust infections and climate projections

To assess the influence of the projected changes in the regional climate conditions in Luxembourg on the development of WLR the statistical relationship describing the evolution of this fungi and the output of the COSMO-CLM model were combined. Only hours during the night and with fulfilled infection conditions were analysed. Figure 3a-c highlights the absolute frequency of mean infections hours per year – varying according to the definition between 12 and 20 h – for the reference period and the two future time spans. Infections hours per night were counted starting on 1 January to 10 July of each year. In all three time slices the absolute frequency of hours with fulfilled infection conditions are higher at Burmerange than at Reuler. Based on the Mann-Whitney Rank Sum Test no statistically significant differences between the two stations could be identified. Also the differences between the reference time span (Fig. 3a) and the near (Fig. 3b) and the far future (Fig. 3c) periods at both stations were not significant.

In Fig. 4a-c a detailed analysis of the frequency distribution of the infections hours throughout the year is shown. The relative frequencies of the occurrence of successive hours

Table 1 Dates (day of year) of first apparition and maximum severity of wheat leaf rust at the selected sites during the 2003–2013 period. The average disease severity on the two upper leaves between GS 75 and GS 87 (Zadoks et al. 1974) is also given

	Burmerange			Reuler		
Year	Day of first apparition	Day of maximum severity	Average disease severity (%)[a]	Day of first apparition	Day of maximum severity	Average disease severity (%)
2003	161	188	74.0 (19.0)	181	188	4.0 (15.0)
2004	166	187	8.0 (1.3)	194	194	0.2 (0.6)
2005	185	185	6.0 (2.0)	nr[b]	nr	nr
2006	122	184	15.0 (3.7)	184	193	1.0 (0.1)
2007	106	176	57.0 (21.0)	155	176	0.1 (0.3)
2008	154	182	5.0 (2.0)	182	196	1.0 (1.0)
2009	131	187	40.0 (20.0)	131	194	3.0 (1.0)
2010	130	186	7.0 (5.0)	179	193	0.1 (0.5)
2011	129	185	9.0 (12.0)	171	185	0.2 (0.7)
2012	129	177	70.0 (27.0)	150	184	2.0 (2.0)
2013	168	175	5.0 (3.0)	175	175	0.3 (1.1)

[a] Numbers in parentheses are the standard deviation

[b] no data recorded (i.e., absence of wheat leaf rust infection)

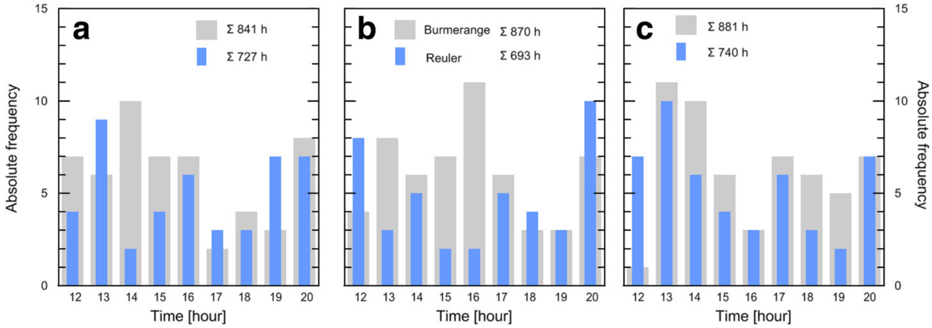

Fig. 3 Histograms of the absolute frequency of the infection hours of wheat leaf rust for a) the reference period (1991–2000), b) the near (2041–2050), and c) the far future (2091–2100) at Burmerange and Reuler

with fulfilled infection conditions were shown per station and for the three different time spans. During the winter season in the reference period at Reuler no hours with fulfilled infection conditions for WLR occurred. This changed under projected climate condition. For the near future up to 15 h and 18 h for the far future with fulfilled conditions were projected. The same pattern could be observed for Burmerange. In general, the shifts towards more and longer periods with infection conditions were more pronounced at Burmerange than at Reuler. Significant differences between the two sides could only be identified for the winter period in the near future ($P = 0.031$).

3.5 Infection periods of wheat leaf rust and potential impacts on grain yield

Attacks of fungal diseases such as WLR or Septoria leaf blotch (SLB) reduce the photosynthetic activity of leaves by accelerating the senescence process. A rapid senescence can affect

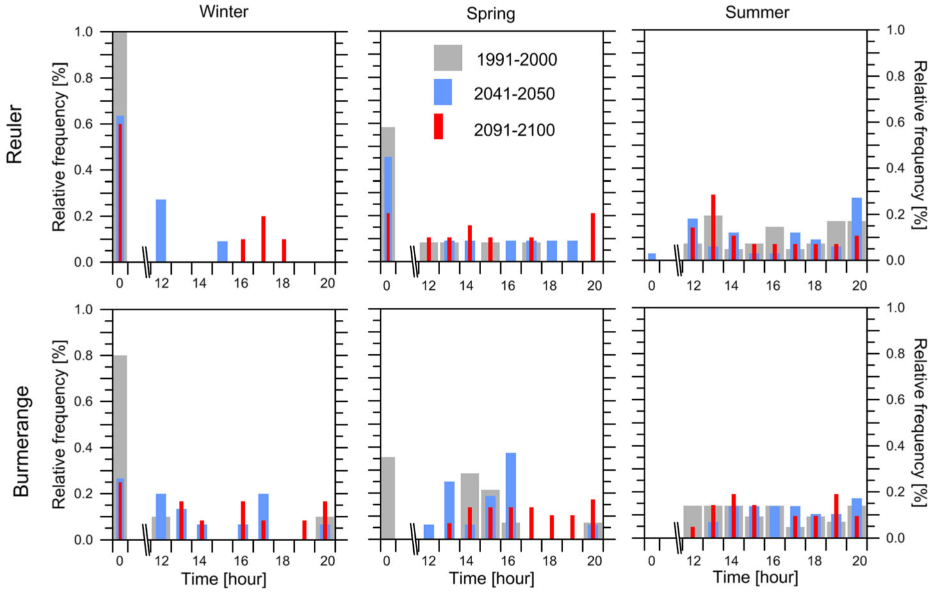

Fig. 4 Relative frequencies of the infection hours of wheat leaf rust for Reuler and Burmerange according to the meteorological season and time slice

adversely the final grain yield. The average severity of predominant fungal diseases along with yield loss (expressed as the difference between assumed optimal fungicide-treated and control plots) at the selected sites during 2003–2013 are given in Table 2. Losses in grain yield ranged from 5 % to 32 % during field experiments, with an average loss of 15 % at both sites. At Burmerange the proportion of WLR infection period in summer for susceptible to highly susceptible varieties (WLR susceptibility ≥7) was significantly correlated to the average WLR disease between GS 75 and GS 87 ($r = 0.64$, $P = 0.04$). Relatively high grain yield loss (>10 %) at this site was in most cases associated with noticeable pressure of predominant diseases (combined average severity ≥60 %). Exceptions included the 2003 cropping season when high combined pressure of WLR and SLB resulted in a 5 % loss, and the 2005 cropping season when relatively low disease pressure during GS 75 and GS 87 resulted in 12 % loss. At Reuler the impact of WLR infection could have been negligible since lower WLR severities compared to SLB and wheat powdery mildew (WPM) were recorded in years with yield loss >10 %, except in 2008 when though average severities were <5 % for the 2 predominant diseases a 24 % loss was recorded (Table 2).

With the projected increase of WLR infection periods in the near (2041–2050) and far future (2091–2100) at Burmerange, it would be more likely that WLR severity will increase accordingly (depending on the presence of *P. triticina* spores in fields and the susceptibility of wheat cultivar sown). Given the short time period of observed data (11 years), indicating a range of yield loss proportion for the projected climate data will be risky. Nevertheless, such WLR severities, associated to the reduction of leaves photosynthetic activity, might impact negatively the final grain yield in noticeable proportion if fields are not treated. Because Reuler is not a WLR-prone region (as shown through the experimental data), increasing infection periods under projected climate conditions would probably lead not to higher WLR severity

Table 2 Infection periods of wheat leaf rust (WLR), severity of predominant fungal diseases, and grain yield loss at Burmerange and Reuler during the 2003–2013 period. The predominant fungal diseases were WLR and Septoria leaf blotch (SLB) at Burmerange, wheat powdery mildew (WPM) and SLB at Reuler (WLR severity was added here for comparison purpose). The disease severity corresponds to the average on the two upper leaves between GS 75 and GS 87

	Burmerange			Reuler			
Year	WLR severity (%)	SLB severity (%)	Yield loss (%)[a]	WLR severity (%)	SLB severity (%)	WPM severity (%)	Yield loss (%)[a]
2003	74	18	−5	4.0	17.0	70	−12
2004	8	30	4	0.2	15.0	30	1
2005	6	14	−12	0.0	22.0	3	4
2006	15	58	−11	1.0	4.0	2	−5
2007	57	77	−20	0.1	52.0	5	−28
2008	5	43	−15	1.0	0.5	5	−24
2009	40	67	−21	3.0	6.0	40	−17
2010	7	36	−12	0.1	0.3	1	3
2011	9	2	−6	0.2	0.2	0	−1
2012	70	30	−32	2.0	30.0	2	−21
2013	5	20	3	0.3	0.03	12	−15

[a] Yield losses are calculated as the difference between assumed optimal fungicide-treated plots (double fungicide treatment) and control plots

and more impact on senescence process and yield loss unless the pattern of spores dispersion changes under those future climate conditions.

4 Discussion and conclusion

Climate changes will affect wheat crop production both in the main processes of plant growth and development and in the occurrences and severities of plant diseases. Studies covering a wide range of regions and crops worldwide show that negative impacts of climate change on crop yields have been more common than positive impacts (IPCC 2014). In Central Europe, precipitation is likely to increase in winter but decrease in summer leading to higher drought frequencies. These conditions will affect the development of plant diseases depending on the region and the crop considered (Bregaglio et al. 2013; Mikkelsen et al. 2015).

In this study we emphasized the potential infection periods of WLR in a changing climate at two selected sites in Luxembourg using a threshold-based model for WLR infection and progress that involves night-time hourly data of air temperature, relative humidity and precipitation (El Jarroudi et al. 2014a; El Jarroudi et al. 2014b). During the field experiments carried out over the 2003–2013 cropping seasons, WLR infections were successfully simulated using this approach. The proportions of favourable days for WLR infection during spring and summer could be potentially harmful to wheat leaves development, and thereby grain yield, when two main conditions are satisfied: presence/dispersion of WLR spores and sustaining weather conditions for the WLR development over a certain period following the infection. At Burmerange both, weather conditions for WLR infection and development were generally met. Six years with relatively high periods of favourable weather conditions conducive to WLR infection during summertime (i.e., 2003, 2004, 2007, 2009, 2012 and 2013) and noticeable disease severities were recorded in four years (exceptions include 2004 and 2013). At Reuler, though the conditions of WLR infection could be met, its development was hampered by the absence of spores (spores dispersion not effective due to the presence of the Ardennes barrier) and the lack of favourable meteorological conditions following infections. Low WLR severity observed on upper leaves could also be related to the cultivar's susceptibility to WLR. At both sites and in years with favourable periods for infection in summer and subsequent low disease development (2004 and 2013), the disease propagation may have played a role in the percentage of severity. In 2013 the sporulation level was very low across the study sites and appeared later in the cropping seasons compared to previous years.

A range of expected changes in air temperature, relative humidity and precipitation could be derived based on a multi model ensembles approach. Our analysis showed that the high resolution COSMO-CLM projection was within the spread of this ensemble and therefore suitable for this impact study. This method has been already successfully used in different impact studies (Matzarakis et al. 2013; Junk et al. 2014). To address the challenges farmers will face under projected climate conditions the dynamics of important crop diseases like the WLR must be understood (Bregaglio et al. 2013). One important assumption we made in our study is that the response of WLR to climate will be the same as now under future climate conditions. We identified different disease levels at the two test side under present climate conditions and in general shifts towards more and longer periods with suitable infection conditions for WLR in the future. Due to these boundary conditions it will be more likely that WLR severity will increase if spores are present in the fields and no significant changes of the susceptibility of the wheat cultivars will occur. These findings of an increasing risk towards

WLR infections are in line with the findings of Dale et al. (2001); Harvell et al. (2002); Launay et al. (2014) or Racca et al. (2015) who showed increasing plant fungal infections under increasing air temperature conditions. But not only trends in meteorological variables will affect future disease risks but also changes in the cropping system will play a major role (Juroszek and von Tiedemann 2015). Therefore, the results of such impacts studies are useful for policy- and decision makers for defining suitable agronomic adaptation strategies like decision support systems, right cultivar choice or shifts in the time of sowing to minimise or avoid negative effects on future crop yields. Fungal infestations in wheat including those caused by WLR occurred where successive wheat crops are grown on retained and infected stubble. Crop rotation and tillage practices could therefore reduce such negative impacts. However, under favourable weather conditions, rust spores are produced in great numbers and they can be blown vast distances by the wind. In such cases these two practices may be of little effect on the build-up of WLR epidemics.

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