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LETTER

Plant pathogen infection risk and climate change in the Nordic and Baltic countries

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Abstract

Climate change and global warming are already affecting food production, and the impact is predicted to intensify in the future. Previous studies have been based on global data and have provided general information about climate change effects on food production. Regional high-resolution data are, however, needed to evaluate the effect of future scenarios of climate change to support strategic and tactical planning to safeguard food production. Here, we provide results on the future potential distribution range of fungal plant pathogens in the Nordic and Baltic countries. This is done using regional climate model data at 12.5 km horizontal resolution. The temperature dependent infection risk and species richness are calculated using data for 80 plant pathogens. Within the region the studied pathogens will in most cases thrive more and be more abundant in a warmer climate; leading to a longer infection risk season and the introduction of new pathogens. This applies to all emissions scenarios, even though the effects are stronger with high emissions. Our results indicate that plant diseases will increase, and this will negatively affect crop production and food security.

1. Introduction

The world is in the middle of an ongoing climate change. The observed global temperature is currently around 1.1 °C higher than in pre-industrial times (WMO 2022; 2023). This warming is mostly fuelled by anthropogenic emissions of greenhouse gases and land-use changes and will continue as long as there are net emissions of greenhouse gases (IPCC 2023). Climate change has already had adverse impacts on ecosystems, people and infrastructure, and a continued global warming will increase these hazards and risks (IPCC 2022). Food production and food security are threatened by climate change; both directly by for example drought stress and floods, and indirectly by pests and diseases (Bezner Kerr *et al* 2022). It has been reported that climate change is already reducing global agricultural productivity (Ortiz-Bobea *et al* 2021). The Nordic and Baltic states is a region experiencing rapid climate change. As a reflection of this, the temperature in Sweden has increased with 1.9 °C since the end of the 19th century — roughly twice the global temperature increase. A large part of this warming occurred between the periods 1961–1990 and 1991–2020 (Schimanke *et al* 2022). This puts special emphasis on the need of urgent climate adaptation of agriculture in this region.

This study specifically looks at the future distribution of plant pathogens in northern Europe. Plant disease is the result of interactions between pathogen, plant host and the local environment mainly including weather factors. This is often referred to as the disease triangle. The fact that plant diseases are affected by climate and weather has been known since ancient times (Orlob 1971, Nevo 1995, Fones *et al* 2020). Temperature is identified as a major driver of plant disease development, and global warming can result in an expansion of areas with a conducive environment for plant pathogens resulting in higher yield losses. This may counteract the yield increases expected from a higher temperature with a longer growing season, in combination with raising levels of atmospheric CO_2 (Raza and Bebber 2022). Since pathogens migrate when the opportunity arises (Gregory *et al* 2009, Fones *et al* 2020), it is predicted that global warming will lead to latitudinal shifts in the distribution of plant pathogens. However, shifts in pathogen distributions do not solely depend on climate, but also on the availability of susceptible host plants (Shaw and Osborne 2011). As a result, changes in cultivation of both established and newly introduced crops due to climate change will play a major role here. Even though the mechanisms governing plant disease development and how these are affected by climate change are known, we can be sure that the future will bring surprises and new challenges. In the study presented here we aim to understand how climate change will impact the temperature-dependent plant pathogen infection risk and species richness in the Nordic (excluding Iceland) and Baltic states. This was done by combining high-resolution temperature data for the present and the future in the region with growth temperature intervals for 80 fungal plant pathogens. The results are discussed in relation to plant disease development and future changes in growing season length for the selected emission scenarios.

2. Material and methods

2.1. Climate models

The data describing present and future climates is based on the EURO-CORDEX ensemble covering Europe with a grid spacing of 0.11°, which approximately equals 12.5 × 12.5 km grid spacing (Jacob *et al* 2014). Within CORDEX a number of global climate models (GCM) are used to force a number of regional climate models (RCM). Every six hours the RCM reads data from the GCM on the boundary of the model domain. Boundary conditions include temperature, air pressure, air humidity and wind at several vertical levels. Climate modelling is computationally expensive which means that GCMs are usually run on relatively coarse horizontal resolutions (typically 100–300 km). RCM simulations can afford higher resolution (typically 5–20 km) since they cover a smaller part of the globe. Even though RCM simulations are governed by the driving GCM RCMs provide new information (e.g. Vautard *et al* 2020, Strandberg and Lind 2021). Topographical features, such as coastlines or mountains, are better described with higher model resolution. Furthermore, RCM simulations give more details and a better representation of physical processes, especially local events like convective rain (e.g. Olsson *et al* 2015, Prein *et al* 2015, Rummukainen 2016).

A benefit of using climate model ensembles, like the CORDEX ensemble, is that it enables a wider set of statistical tests. If only one model simulation is used, it is not possible to know how that simulation relates to other simulations, using other models or different scenarios. Furthermore, one simulation is not enough to estimate model sensitivity to emissions of greenhouse gases, or natural variability (e.g., Christensen and Kjellström 2020; 2021). The EURO-CORDEX RCMs used here are forced by GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor *et al* 2012). They are evaluated using observations and are judged to perform well in the climates of the 20th and 21st centuries (e.g., Vautard *et al* 2020, Coppola *et al* 2021).

In this study we used an RCM ensemble consisting of 17 GCM-RCM combinations that are available for the emission scenarios RCP2.6, RCP4.5, RCP8.5 (Supplementary table S1). This ensemble cannot capture the full spread of the CMIP5 GCMs, and since it is only using one simulation per GCM-RCM combination it cannot describe the full extent of natural variability. It is, however, an ensemble that is large enough to admit uncertainty estimates, and it is the largest possible ensemble that is consistent across the three emissions scenarios. To minimise systematic errors the RCM data are bias adjusted using the MIdAS method (Berg *et al* 2022). When performing bias adjustment observations are used to correct systematic deviations in model data without losing the trend and variability.

Using different scenarios is a good way to assess the potential spread and effects of future climates. We can be more or less sure that the temperature increase given by RCP2.6 will occur within this century; probably around 2040 given the global trend of 0.2 °C per decade IPCC 2018). Following the same trend, the temperature increase given by RCP4.5 is likely to occur in the end of the century. The emissions in RCP8.5 is less likely, but the temperature increase could potentially occur should the climate system be more sensitive to changes in greenhouse gases than expected, or in the absence of climate change policy (Riahi *et al* 2011). Here, RCP8.5 is used as an upper limit of what is probable.

The emission scenarios used here can very simplified be described as: RCP2.6: Greenhouse gas emissions culminate at year 2020 and declines to reach net-negative emission at the end of the 21st century. RCP4.5: Emissions culminate around 2040 to then decline to reach half the levels from 2050 at 2100. RCP8.5: Emissions continue to increase to the end of the century (Moss *et al* 2010, van Vuuren *et al* 2011). The global temperature increase between 1986–2005 and 2081–2100 is on average 1.0 °C (RCP2.6), 1.8 °C (RCP4.5) and 3.7 °C (RCP8.5) respectively (IPCC 2013).

The temperatures used are the model ensemble means. For each scenario this is the average of the model ensemble over a chosen 30-year period. To catch the model spread the 10th and 90th percentiles of the ensemble are also calculated.

The growing season length (GSL) is the number of days from the first day until and including the last day of the growing season (GS). The GS starts at the first consecutive six-day period with daily average temperature > 5 °C. The first day of the GS is the first of these six days. The GS ends after July 1 at the first consecutive six-day period with daily average temperature < 5 °C. The end of the GS is the day before this six-day period.

2.2. Calculation of temperature dependent pathogen infection risk and species richness

Plant diseases are caused by different types of pathogenic microorganisms, predominantly fungi. Each fungus has a specific temperature interval for growth, where the minimum (T_{min}) and maximum (T_{max}) growth temperature defines the lower and upper temperature limits for growth. The optimal temperature (T_{opt}) designates the temperature at which the growth-rate is highest. We calculated the temperature-dependent infection risk $r(T)$ in the Nordic (excluding Iceland) and Baltics, according to Chaloner *et al* (2021) (Supplementary equation 1). For the calculations, we used the same set of plant pathogens selected by Chaloner *et al* (2021), as they provide temperature data for the most significant fungal diseases across a broad range of plant hosts. At T_{opt} $r(T) = 1$. If the temperature goes below T_{min} or above T_{max}, then $r(T) = 0$. In this study we calculated $r(T)$ for 80 pathogens for which temperature intervals exist (Chaloner *et al* 2021). Pathogen species richness, R_r, is defined as the number of pathogens with $r(T) \geqslant 0.5$ in a particular time and place under specific temperatures (Chaloner *et al* 2021).

Calculating $r(T)$ and R_r based on climate model data was done in the following way: For each month (i) and grid cell (j) a climate model ensemble mean was calculated together with the 10th and 90th percentiles of the same ensemble. This means that, when calculating $r(T)$, $T\{i,j\}$ is the model ensemble mean (or percentile) temperature in every month (i) and grid cell (j). Thus, for every month, grid cell and emission scenario there are three values for $r(T)$ for each pathogen, and three calculations of R_r. This was done for the scenarios RCP2.6, RCP4.5 and RCP8.5. Within climatology it is practice to use 30 year periods to even out short-time variability. We use 1971–2000 as a reference, and the three adjacent periods 2011–2040, 2041–2070 and 2071–2100 to express future climate change on different time scales.

3. Results

3.1. Climate change

The projected ensemble mean annual temperature is estimated to increase in the 21st century according to the three chosen emissions scenarios (figure 1). The warming pattern within the studied region shows two distinct features. Firstly, the warming is larger in the north than in the south and larger in winter than in summer (see supplementary figure S1 for maps of individual months). Secondly, all models project warming across the domain in all emission scenarios. The pattern of change is the same in all time periods and scenarios, but the amplitude of change is larger with larger amounts of emissions. The difference between the scenarios is small in the beginning of the century and increases with time. In the period 2011–2040, the projected temperature increase is 1 °C–3 °C in all scenarios. In 2071–2100 the temperature increase in RCP2.6 is still 1 °C–3 °C (albeit with a larger area of over 2 °C); RCP4.5 give 2 °C–4 °C and RCP8.5 4 °C–6 °C, and even more than 6 °C in parts of northern Sweden and Finland (figure 1). The increase in temperature is reflected in the growing season length (GSL), which is expected to increase between 10–30 days in RCP2.6, 20–70 days in RCP 4.5 and 60–100 days in RCP8.5 by the next century (figure 2).

3.2. Temperature dependent infection risk r(T)

Temperature dependent pathogen infection risk $r(T)$ was calculated using the projected future temperatures. Since it is not possible to show maps for all 80 pathogens, we selected three pathogens to illustrate the effect of $r(T)$ changes. The selected pathogens (*Fusarium graminearum and Puccinia striiformis*) cause important diseases in wheat, an important current crop relevant to the areas. The third selected pathogen, *Phakopsora pachyrhizi* is an important disease in soybeans, a crop which is expected to be introduced in the region as temperatures increase. The change in $r(T)$ for the selected pathogens serves as examples of expected outcomes of increasing temperatures. At high latitudes it is expected that a warming will give an increased $r(T)$ since the pathogens in this region are limited by low temperatures. The most common pattern among the 80 pathogens in the dataset is exemplified by the infection risk of *F. graminearum* (figure 3(a)), the cause of Fusarium root rot and Fusarium head blight, the latter connected with mycotoxin production (Karlsson *et al* 2021). In the historical period (1971–2000) the $r(T)$ season of *F. graminearium* spans from May to September and the $r(T)$ is highest in July with values of up to 0.8 in most of the Baltic states, parts of southern Finland and southeast Sweden. In Norway

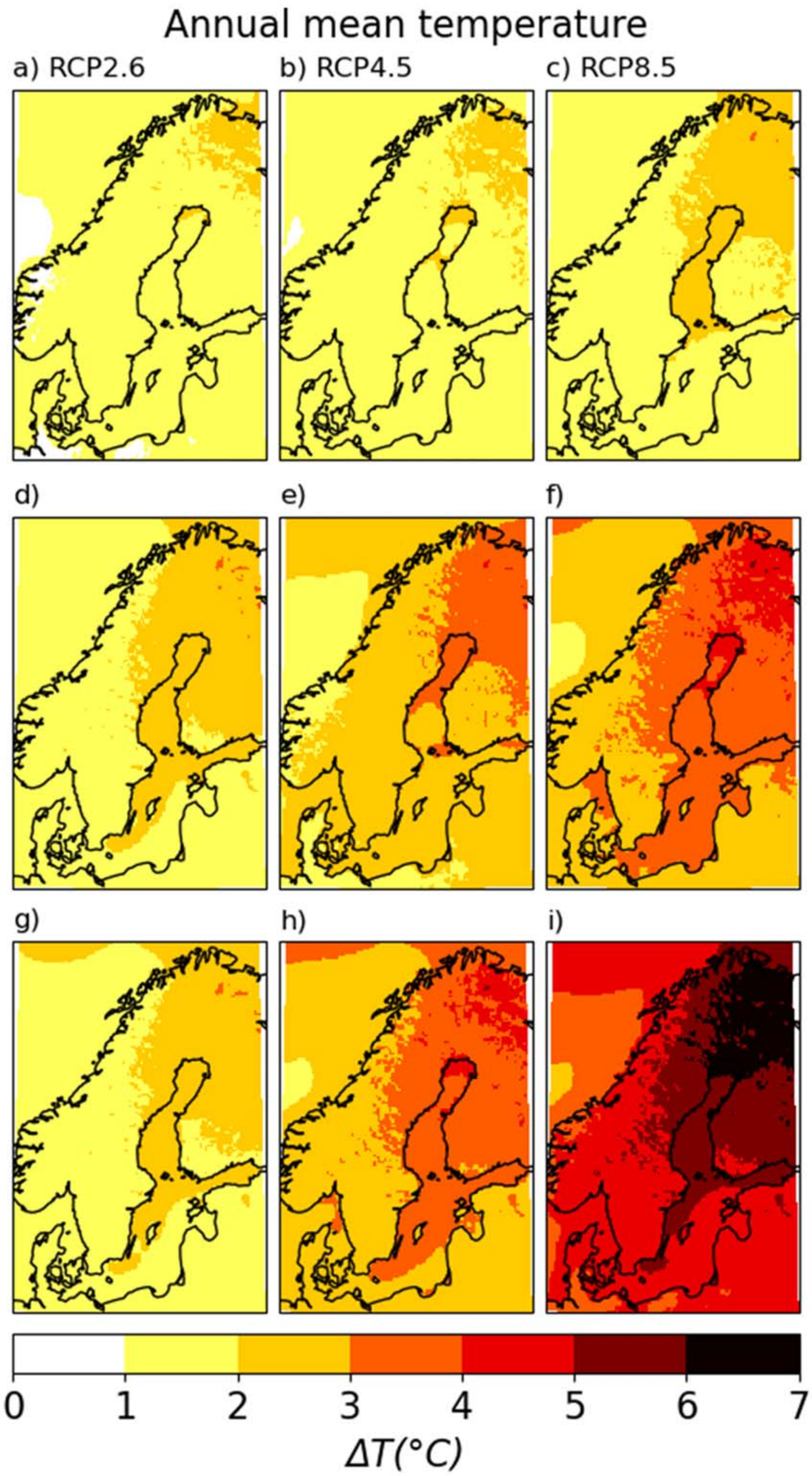

Figure 1. Projected ensemble mean annual temperature increase (°C) relative to the period 1971–2000 at 2011–2040 (a)–(c), 2041–2070 (d)–(f) and 2071–2100 (g)–(i) according to emission scenarios RCP2.6 (a), (d), (g), RCP4.5 (b), (e), (h) and RCP8.5 (c), (f), (i).

and northern Sweden $r(T)$ is below 0.5. July $r(T)$ is above 0.9 according to RCP2.6 in most of the southeastern half of the domain in 2071–2100; for RCP4.5 $r(T) = 1$ in Denmark, the Baltic states, and the southern parts of Sweden and Finland. The $r(T)$ of *F. graminearum* increases with higher temperature, and the season starts earlier in the northern parts of the region.

In a few cases, increased temperatures result in a decreased $r(T)$ at high latitudes. As an example, *P. striiformis*, causing yellow rust in wheat (figure 3(b)), has values of $r(T)$ in the range of 0.8–1 in almost the entire domain in 1971–2000 during the period May — September except for June when values are somewhat lower (figure 4). In a warmer climate $r(T)$ is projected to decrease during summer to even fall below 0.5 in June. This is

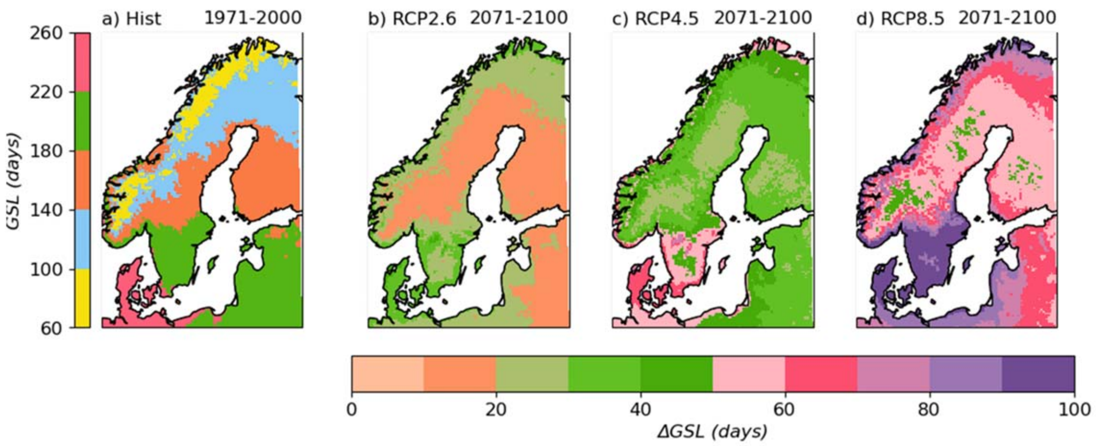

Figure 2. The growing season length (GSL) is presented in days, where (a) illustrates the GSL in the period 1971–2000 and b-d the projected difference of GSL in days in 2071–2100 according to emission scenarios RCP2.6 (b), RCP4.5 (c) and RCP8.5 (d) relative to 1971–2000.

seen in RCP2.6, but to a larger degree in RCP4.5 and RCP8.5. On the other hand, the season starts earlier. April and October are seeing an increase in $r(T)$ of 0.1–0.2 already in RCP2.6. In October, this means $r(T)$ values of up to 1 in large parts of Sweden and the Baltic states.

A third example of $r(T)$ changes caused by temperature increase is based on *P.pachyrhizi*, causing soybean rust (figure 3(c)). Soybean rust *P. pachyrhizi* is a major problem in soybean production under the current crop distribution (Goellner *et al* 2010). In the historical climate (1971–2000) this pathogen displays a practically non-existing temperature-dependent infection risk. At 2071–2100 $r(T)$ is still projected to be low according to RCP2.6 (0–0.5) but rising above 0.5 in mainly parts of Finland and the Baltic states in July according to RCP4.5 (figure 5). The increased risk area in future climate potentially overlaps with the future distribution of soybean production areas.

Supplementary figures S4-S83 show $r(T)$ maps for all 80 pathogens.

3.3. Pathogen species richness R_r

The effect of a warmer climate on the distribution of plant pathogens species richness (R_r), defined as the proportion of the 80 pathogens in the growth temperature dataset with $r(T) \geqslant 0.5$ was calculated (figure 4). R_r spans between 0 (none of the pathogens can survive) to 80 (all pathogens can survive). In the historical period (1971–2000) the period of R_r values above 0 spans the months May–September. The species richness is highest in July with values from 60 in parts of the Baltic countries to below 20 in the Scandinavian mountains. With climate change and warmer temperatures R_r values will increase since $r(T)$ values in most cases increase with higher temperatures. RCP2.6 show R_r values of over 60 in July in large parts of southern Sweden, southern Finland and the Baltic states in 2071–2100. Within the same time frame R_r will have a monthly increase of around 10 from May to September. In RCP4.5 R_r exceeds 60 in Denmark, Southern Sweden and the Baltic states in both July and August and in southern Finland in July. There are also land areas with R_r values over 10 in October. In RCP8.5 R_r values even reach above 70 in some parts of the domain. See supplementary figures S2 and S3 for corresponding maps of the periods 2011–2040 and 2041–2070.

In order to take the time dimension, interannual variability and the spread of the climate model ensemble into account, we looked in more detail at R_r in four locations within the domain; southern Sweden, northern Sweden , Finland and the Baltic States. Already in the period 2011–2040, the R_r in July show clear differences compared to the historical period (figure 5). These differences increase with time and with the emission scenario. The distance between the 10th and 90th percentiles in R_r is around 30 at all locations. This distance decreases at the locations with relatively warmer climate (Southern Sweden, the Baltic States) when the 10th percentile increases more than the 90th percentile.

4. Discussion and conclusions

It is clear that the Nordic and Baltic States will continue to experience warming for several decades. In addition, the climate change effects are elevated at higher latitudes, as shown by the temperature increase in Sweden which is roughly twice the global temperature increase (Schimanke *et al* 2022). With the changing climate, it is expected that the cropping seasons in the region will be prolonged by an earlier start and a later end (figure 2). This will

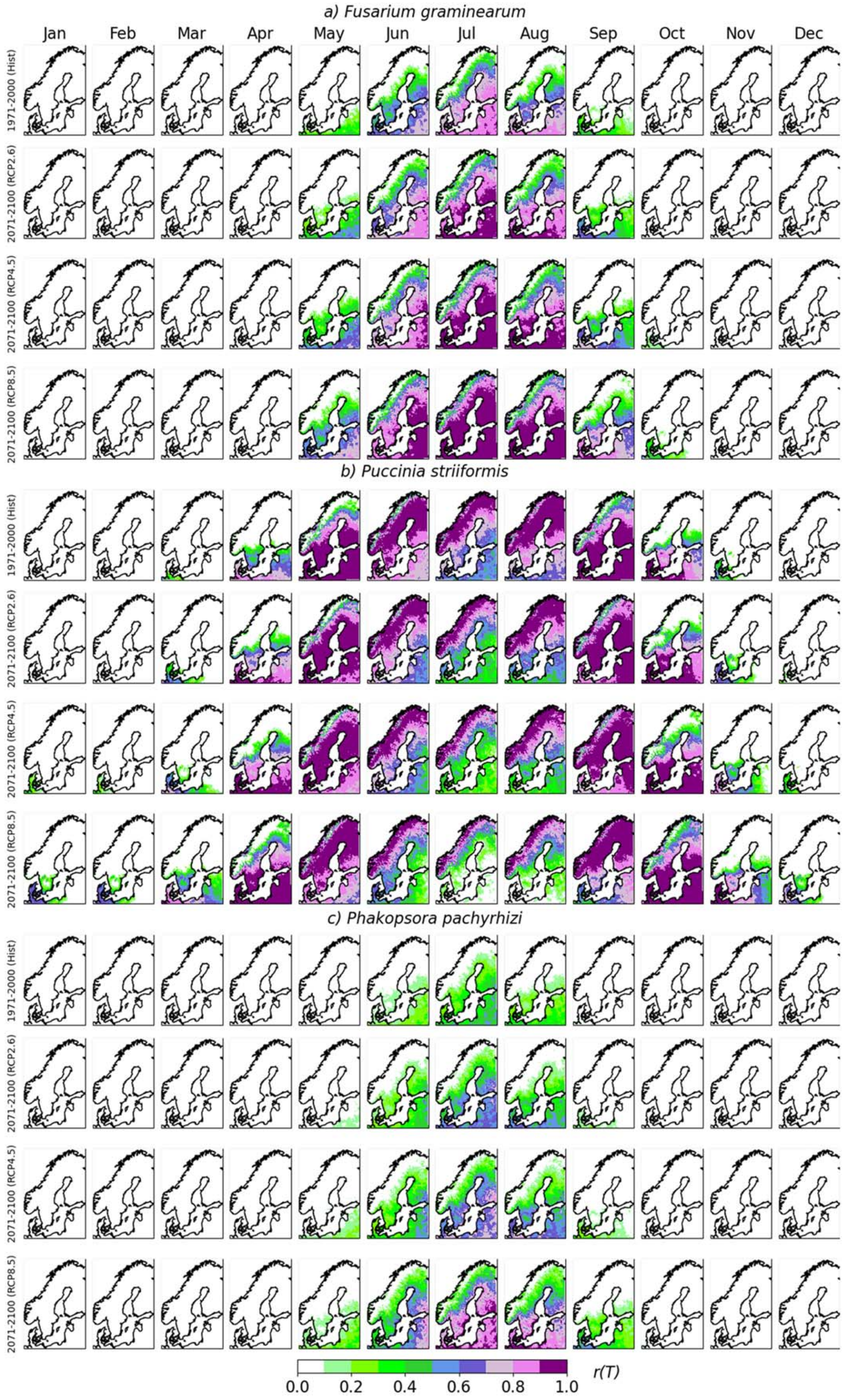

Figure 3. Temperature dependent pathogen infection risk $r(T)$ in each month for (a) *Fusarium graminearum*, (b) *Puccinia striiformis* and (c) *Phakopsora pachyrizi* for 1971–2000 (top rows) and 2071–2100 for RCP2.6 (second rows), RCP4.5 (third rows) and RCP8.5 (fourth rows). The colours correspond to the different values of temperature-dependent infection risk $r(T)$. Only land points are shown.

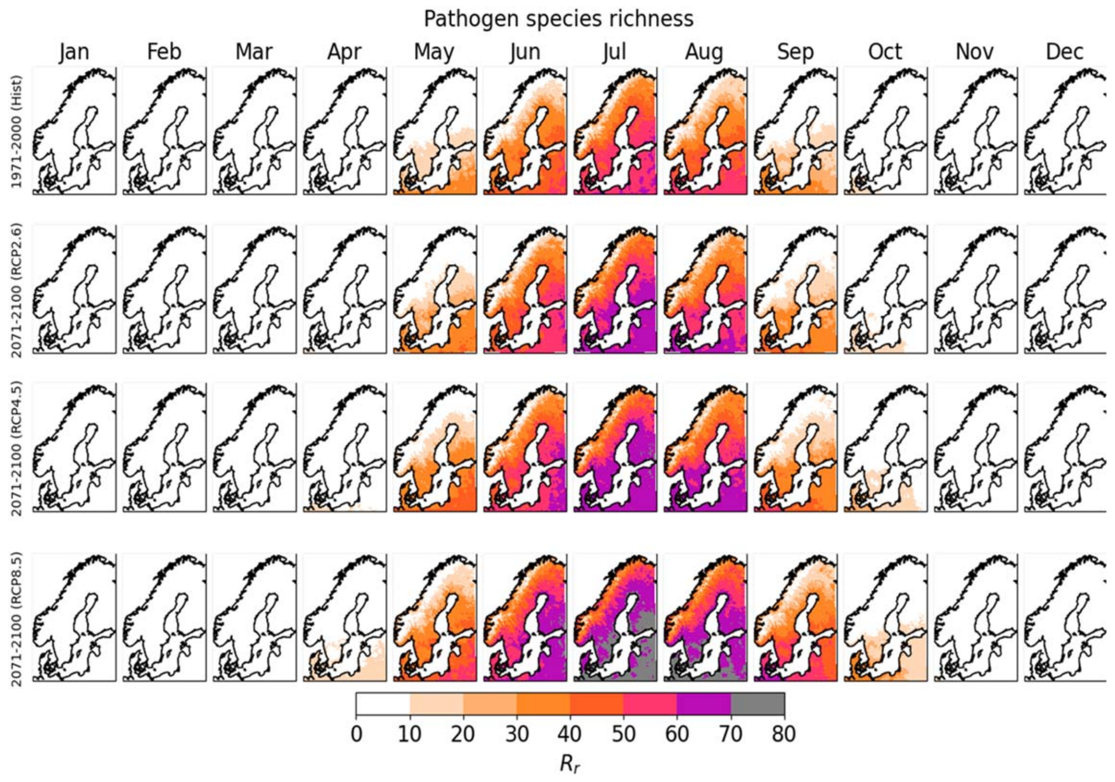

Figure 4. Pathogen species richness R_r in all months for 1971–2000 (top row) and 2071–2100 for RCP2.6 (second row), RCP4.5 (third row) and RCP8.5 (fourth row).

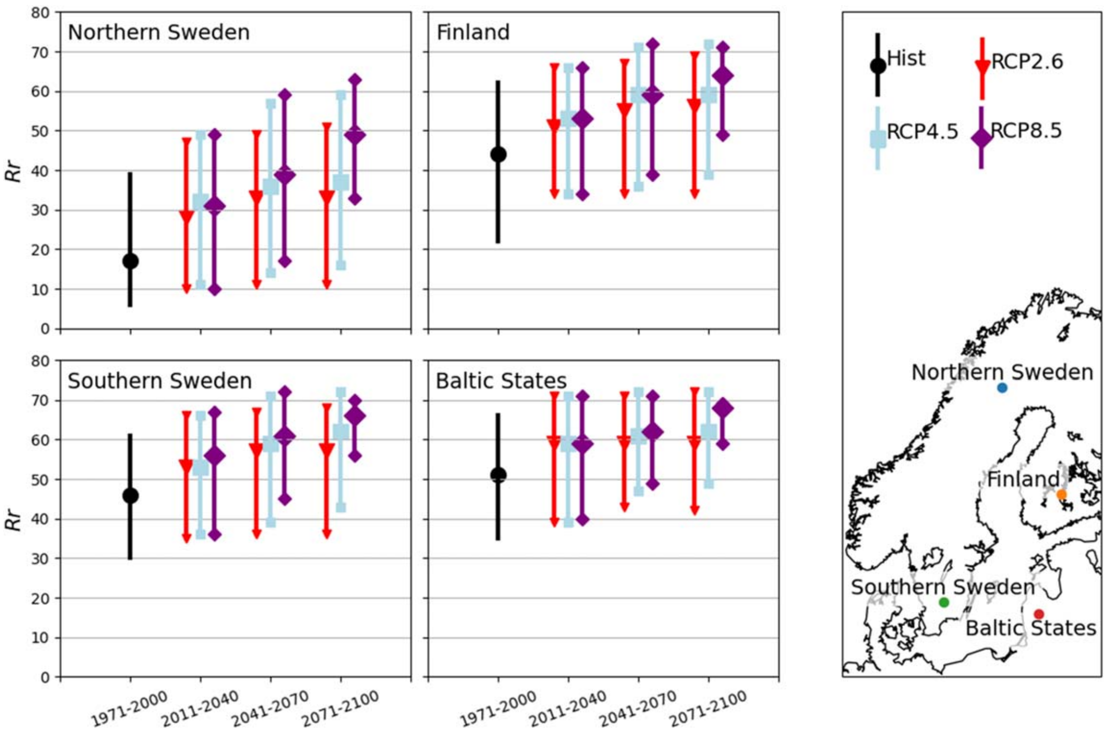

Figure 5. Pathogen species richness R_r in July at four locations, southern Sweden, northern Sweden, Finland and the Baltic States in 1971–2000, black dots; and 2011–2040, 2041–2070, 2071–2100 for RCP2.6, RCP4.5, RCP8.5 (red triangles, blue squares and purple diamonds respectively). The central marker shows the ensemble average, lines span the distance between the 10th and 90th percentiles. The locations are marked in the map.

affect the distribution of both already established and newly introduced crops. A general conclusion is that good crop conditions match the conditions that are favourable for pathogens damaging the crop. At northern latitudes, like the region studied here, increased temperatures mostly mean that the conditions for plant pathogens become more favourable. Here we show a clear relationship between increased temperature, increased plant pathogen temperature dependent infection risk $r(T)$ and increased species richness R_r, leading to changes in pathogen abundance (figure 5). All scenarios, including the one with reduced greenhouse gas emissions, show a clear warming trend. Thus, a conclusion is that the question is not if the risk of infection from plant pathogens will increase, but how much it will increase.

4.1. Emission scenarios and temperature change

The linear relationship between temperature change and the three emission scenarios is interesting, indicating that the effect of long-term small emissions can be used as a proxy for short-term large emissions, or vice versa. For example, the temperature change in long-term (2071–2100) with small emissions (RCP2.6) (figure 1(g)) is very similar to short-term (2011–2040) changes with large emissions (RCP8.5) (figure 1(c)); and long-term changes with medium emissions (RCP4.5) (figure 1(h)) to mid-term (2041–2070) changes with large emissions (RCP8.5) (figure 1(f)). This means that we can use the three scenarios at 2071–2100 as a way of describing the possible limits of climate change. The temperature increase projected in RCP2.6 will most likely occur, even if we cannot say exactly when. The temperatures in RCP4.5 will likely occur in the end of the 21st century, even though it could be avoided with policy changes. RCP8.5 could be seen as an extreme upper limit.

4.2. Change of potential pathogen distribution

This study shows that the temperature dependent infection risk increases for the studied plant pathogens and that the season for infection risk is prolonged. Consequently, the pathogen species richness, R_r, (considering 80 plant pathogens) in July increases from 30–60 to 40–70. The exact number depends on the location, as the number varies with latitude. Already emissions scenario RCP2.6, with a limited warming, shows a clear increase in Rr. According to scenario RCP4.5 R_r in July will be more than 60 in Denmark, the Baltic states and the southern halves of Sweden and Finland. In RCP8.5, indeed an extreme scenario, R_r is even more than 70 in parts of the domain (figure 4).

Higher temperatures increase the potential plant disease damage by giving an earlier start and later end to the 'risk season'. The area with a high temperature-dependent infection risk also expands northward. However, in some instances, like for *Puccinia striiformis*, the infection risk decreases in summer due to high temperatures. Our findings suggest that the pathogen *P. striiformis*, causing yellow rust, seems to become less important during the current wheat growing periods in the Nordic and Baltic states. However, this could be questioned, given that plant pathogens constantly evolve to adapt to changes in the environment and host susceptibility (Möller and Stukenbrock 2017, Zhan and McDonald 2011). In the example of *P. striiformis*, a recent study by Gardner *et al* (2023) showed that the pathogen recovered from heat stress more rapidly than previously anticipated. This is in line with previous studies that have demonstrated that plant pathogens have the capacity to evolve to tolerate higher temperatures and at the same time cause more disease (Milus *et al* 2009). In addition warmer winter temperature will effect pathogen survival between growing seasons (Gladders *et al* 2007). Extreme weather events such as heat waves can favour certain linages, resulting in a shift in temperature preference within pathogen populations.

4.3. Impact on disease in relation to changes in cropping season

Climate change is expected to prolong the growing season at higher latitudes (figure 2), causing shifts in cropping seasons and resulting in changes in sowing and harvesting dates. This may lead to plant diseases occurring at different times of the year than they currently do. It is possible that the timing of sowing and harvesting in different crops will be synchronized with future temperature-dependent infection risk, since it is commonly assumed that good crop growth conditions are also favourable for the pathogen. The impact of higher temperatures on the crop will be a factor, such as inadequate vernalisation of autumn sown crops. Although not included in this study, it is known that a changing climate will alter weather variability. These effects of climate change will pose additional challenges for crop production and are expected to cause local problems such as too much or too little water at different stages of the cropping season. This will require local adaptations to unpredictable events that affect plant health. Therefore, changes in cropping seasons and the introduction of new crops are likely to increase the complexity of pathogen responses and disease risk.

4.4. Final remarks

This study does not claim to provide a comprehensive picture and should be regarded as a first attempt to forecast infection risk and pathogen species richness. A limitation of our study is that it solely focuses on temperature dependent infection risk, leaving out other factors influencing the pathogen distribution such as evolution, changing pattern in rainfall and impact of increasing CO_2. However, many genera of plant pathogens are mainly temperature dependent and relatively unaffected by precipitation, while the development of others is to larger extent driven by precipitation and relative humidity (Raza and Bebber 2022). It is essential to note that infection risk is not the same as disease outbreak. This study suggests that increasing temperature are likely to increase the negative impact of plant diseases. The damage from plant diseases on individual fields is also affected by agronomy and farming practices, which are factors that go far beyond the physical and biological mechanisms studied here. In addition, a future climate is assumed to have an increased frequency of extreme weather events, making it more challenging to manage diseases in a sustainable and need-based way.

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Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

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Ethical statement

No sensitive data were used in this project, no studies were made on humans or animals.

Data availability

Data are available on request from the authors. This paper is also accompanied by a supplementary material.

Author contributions

Gustav Strandberg: Conceptualization, Methodology, Formal analysis, Investigation, Writing—Original draft, Visualization **Björn Andersson:** Conceptualization, Investigation, Writing—Review & Editing **Anna Berlin:** Conceptualization, Investigation, Writing—Review & Editing, Project administration, Funding acquisition

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