An approach to estimate climate suitability for *Phytophthora ramorum* and *Phytophthora pluvialis* across the UK.

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Contents

Executive summary

- This report and the associated web tool have been developed to provide easily accessible estimates of the spatial and temporal suitability of climate for *Phytophthora ramorum* and *Phytophthora pluvialis* across the UK.

- This report details the methodologies used to estimate climate suitability indices for *P. ramorum* and *P. pluvialis*. Sensitivities of the pathogens to daily climate variables (temperature and relative humidity) derived in previous studies were used with 1km gridded UK climate data to estimate the indices across the UK.

- Accompanying the report is an interactive web tool (‘*Phytophthora* climate risk tool’, https://hadleyserver.metoffice.gov.uk/Phytophthora/), developed to enable users to explore the *P. ramorum* and *P. pluvialis* indices and the associated climate data across the UK from 1991 to 2021. Further years can be added in future if required.

- Information provided *via* the web tool can support the understanding and management of risks to UK trees and ecosystems posed by the *P. ramorum* and *P. pluvialis* pathogens.

- Daily changes in climate can also be compared with the number of suitable days per month for individual years and regions, enabling users to make general assessments of the timing of suitable conditions in regions of interest and understand if the locations most at risk from these pathogens are shifting significantly due to climate variability or remaining relatively constant from year to year.

- The web tool provides functionality for the mapped data to be downloaded for inclusion into reports and/or layered with other relevant information, e.g. pathogen observation data. This enables users to undertake more detailed analyses, including to understand the potential of compound risks from both pathogen and other risk factors across the UK.

- This initial study could be improved upon for future developments by:
    - Comparing *P. ramorum* and *P. pluvialis* risk indices with other risk indices,
    - Including observations where the pathogens have been observed across UK,
    - Adding further *Phytophthora* species, where risk indices are available,
    - Including other relevant information on the web tool, e.g. vulnerable plant species,
    - Adding higher-resolution detail for high-risk areas, e.g. topographic or microclimate,
    - Including indices estimated with future climate change scenarios to enable understanding of the potential future severity and changes in risk.

- Further developments to the methodologies and web tool would need to be conducted in collaboration with a wide range of Plant Health and particularly *Phytophthora* experts and co-designed with the organisations and individuals who are responsible for managing these risks to ensure robust scientific estimates of risk are provided in a way that is most useful and useable by the users.

1. Introduction

The project was initiated by Defra to produce an online web-based tool that would illustrate the risk of infection/development of two pathogens of trees that are of regulatory importance. One of the pathogens, *Phytophthora ramorum* (popularly known as Sudden Oak Death or SOD in USA), has been present in the UK since at least 2004 (Brasier *et al*., 2004) and continues to be an economic threat to woodlands (Drake & Jones, 2017). In the USA, there is an asynchrony between the infective stage of *P. ramorum* and the susceptible stage of the host plant species, and it is therefore considered unlikely, given the current conditions, to pose a high risk outside of forests in California and Oregon (USDA, 2023). However, in Europe, by 2009 this pathogen had jumped host to larch trees (*Larix* spp.) and in the UK it is frequently referred to as Sudden Larch Death (SLD) (Brasier & Webber, 2010).

The second pathogen, *Phytophthora pluvialis*, was first detected in 2021 during routine woodland surveys in the far south-west of UK and has been classified as a quarantine pest. Like *P. ramorum*, *P. pluvialis* has a widespread global distribution and has been reported as the cause of red needle cast disease on pine species in New Zealand (Dick *et al*., 2014).

Akin to the approximately 200 described species of *Phytophthora, P. ramorum* and *P. pluvialis* are completely reliant on liquid water for production of spores and dispersal of propagules and favour specific temperature ranges. This association with weather conditions has led to the development of multiple warning schemes which aim to provide forecasts of impending infection following favourable weather conditions. One well-known and studied example is a scheme for *P. infestans,* the causal agent of potato late blight disease (Smith, 1956; Schrödter & Ullrich, 1967; MacKenzie, 1981; Taylor *et al*., 2003). Unlike *P. infestans*, which attacks an annual crop, the pathogens in this project may be much slower to exhibit symptoms as they attack perennial and woody hosts. Weather conditions that favour infection will not necessarily coincide with the appearance of symptoms. There is a distinction to be made between aerially dispersed *Phytophthora* spp. such as those targeted in this project and other *Phytophthora* spp. which are soil based and attack their hosts through the roots. The approach of quantifying risk using above ground weather variables would not be suitable for soil-borne *Phytophthora* pathogens.

The current project aims to use similar indices for *P. ramorum* and *P. pluvialis* as those used to assess *P. infestans* risk (noted above). A long time series of gridded weather variables are used to establish the historical and spatial context of risk from the pathogens. These can be compared to the current monthly/seasonal conditions to estimate how severe and where the risk is developing in near real-time *via* the online web tool.

For *P. pluvialis*, the work in this project is breaking new ground and should help refine where and when to survey for *P. pluvialis* and how significant this disease is likely to be now and in the future. Whereas, for *P. ramorum*, other studies have already developed models to estimate risk factors (e.g., Meentemeyer *et al*., 2011), and it is not clear from this project if or how the risk indices developed here compare with those developed in previous work. Further work would be needed to compare the different approaches for estimating *P. ramorum* risk and assess their suitability for managing the disease.

2. Methods

2.1. Climate/weather indices

Work has been carried out at several locations in both laboratory and field-based studies to quantify how parameters such as temperature and rainfall influence the pathogens in a quantifiable way. For *P. pluvialis* the concurrence of daily maximum air temperature between 15ºC and 20ºC and a daily rainfall quantity > 2mm were linked to sporulation and most rapid mycelial growth (Reeser *et al*., 2013; Dick *et al*., 2014; Hood *et al*., 2014). For *P. ramorum* a more sophisticated (as least in terms of the mathematics) response surface model has been proposed that combines daily temperature and duration of relative humidity (RH) values >= 90% (Tooley *et al*., 2009; Tooley & Browning, 2015; Tooley & Browning, 2016). A caveat is that the cited work was carried out on a single clonal lineage which is uncommon in UK / Europe, and this may have some influence on the scale of the environmental factors on the pathogen. Weather monitoring and the establishment/spread of SLD on UK populations was carried out as part of a Defra project in 2002-2005 (Turner *et al*., 2005).

2.2. Gridded weather data

The UK Met Office Hadley Centre for Climate Science and Services has supported use of the HadUK-GRID dataset of daily weather parameters at 1km grid resolution covering the entire UK (Hollis *et al*., 2019). The grids are derived from observed data and the UKMO's gridding algorithms. For this project, the time-period examined covered 1991 to 2021, which is 11,322 days of data for each parameter. These data are freely available to download from the Centre for Environmental Data Analysis (https://catalogue.ceda.ac.uk/) and are in network common data format (netCDF) a commonly used file format that enables multi dimension datasets to be accessed by freely available tools such as the R programming language (https://www.r-project.org/about.html). Each netCDF file contains the days for a particular month so the three dimensions in this case are the X and Y grid (900 and 1450 cells respectively) and the days of each month as the time dimension.

An example of one of the daily gridded data files is illustrated below for a day in May 2021. There is no significance to the date, it is just one of the many days available (**Error! Reference source not found.**).

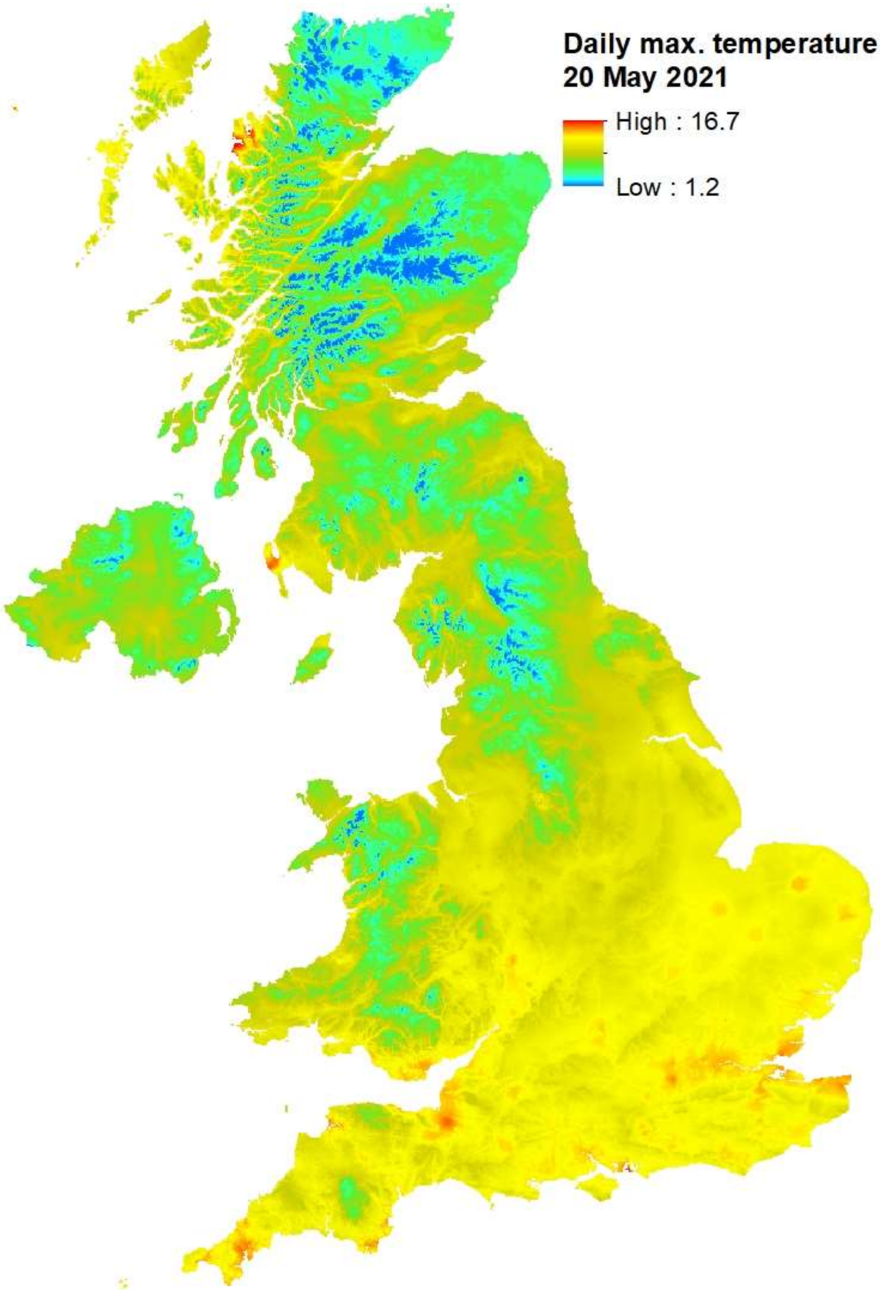


Figure 1. Example of daily maximum temperature (ºC) for 20th May 2021. The full extent of the data includes Orkney and Shetland to the north, but the image has been cropped so it appears larger in the document.

2.3. Application of disease risk index for *Phytophthora pluvialis*

To compile a risk index for each day, an R program was written to extract the cells that had a coincident daily maximum temperature between 15ºC – 20ºC and a daily rainfall > 2mm. The results for each of the daily input grids were written out to a new netCDF file which contains the cells that met the criteria and those that did not. Some days would not have any cells meeting the criteria while other days could have many (**Error! Reference source not found.**).

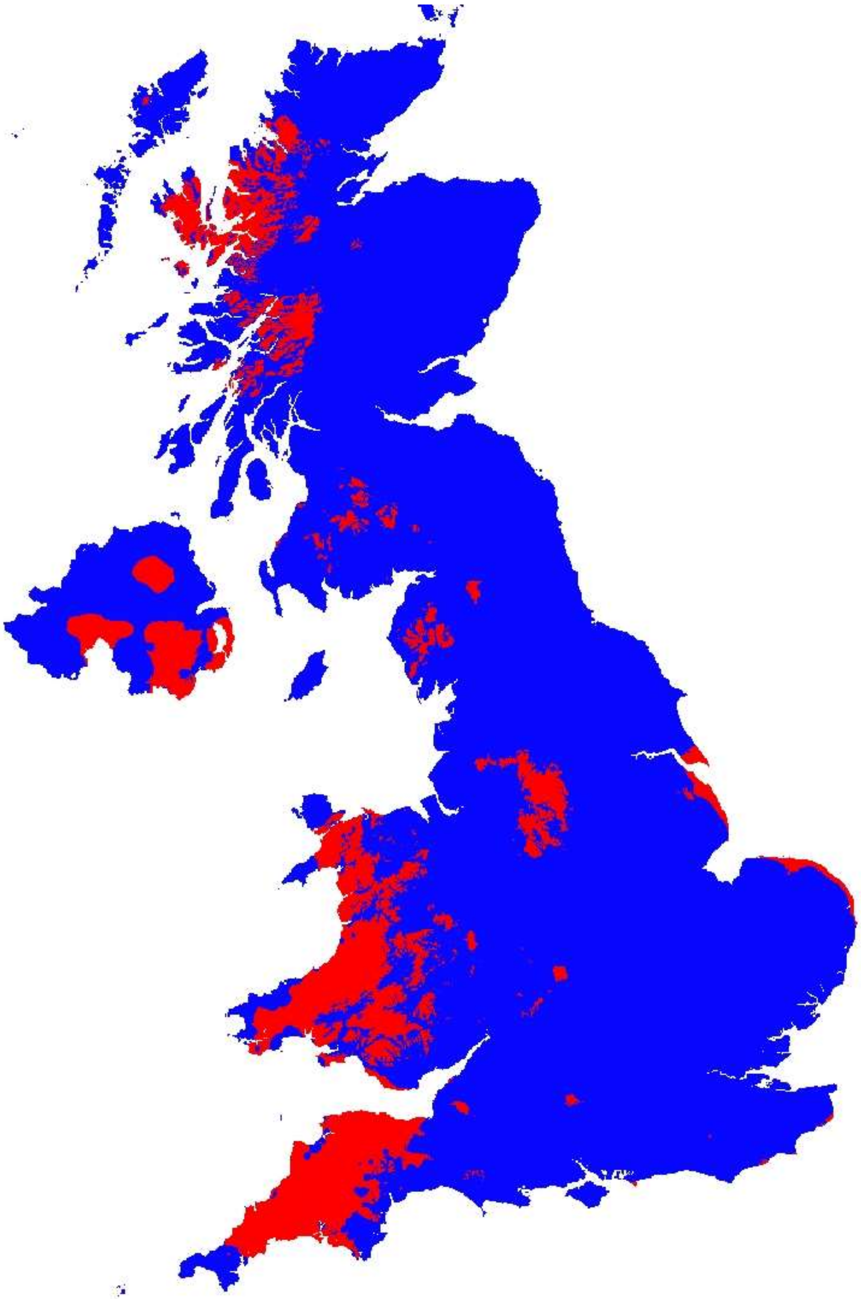


Figure 2. Grid cells which met combined criteria for *Phytophthora pluvialis* (red) and those that did not (blue) on an example day (17th June 2020).

Once all the 11,322 daily grids had been coded as 0/1 then a further R program used these grids to sum a total for each month for the 30-year period. Some months would have a sum of zero cells meeting the criteria while others have a range of values, although none greater than the number of days in the month (Error! Reference source not found.).

For the period 1991 – 2021, there are 372 monthly netCDF files containing the summed values of the days where the criteria were met which will feed the web tool with the historic risk of *P. pluvialis* that can be expressed as a monthly, seasonal, or annual basis.

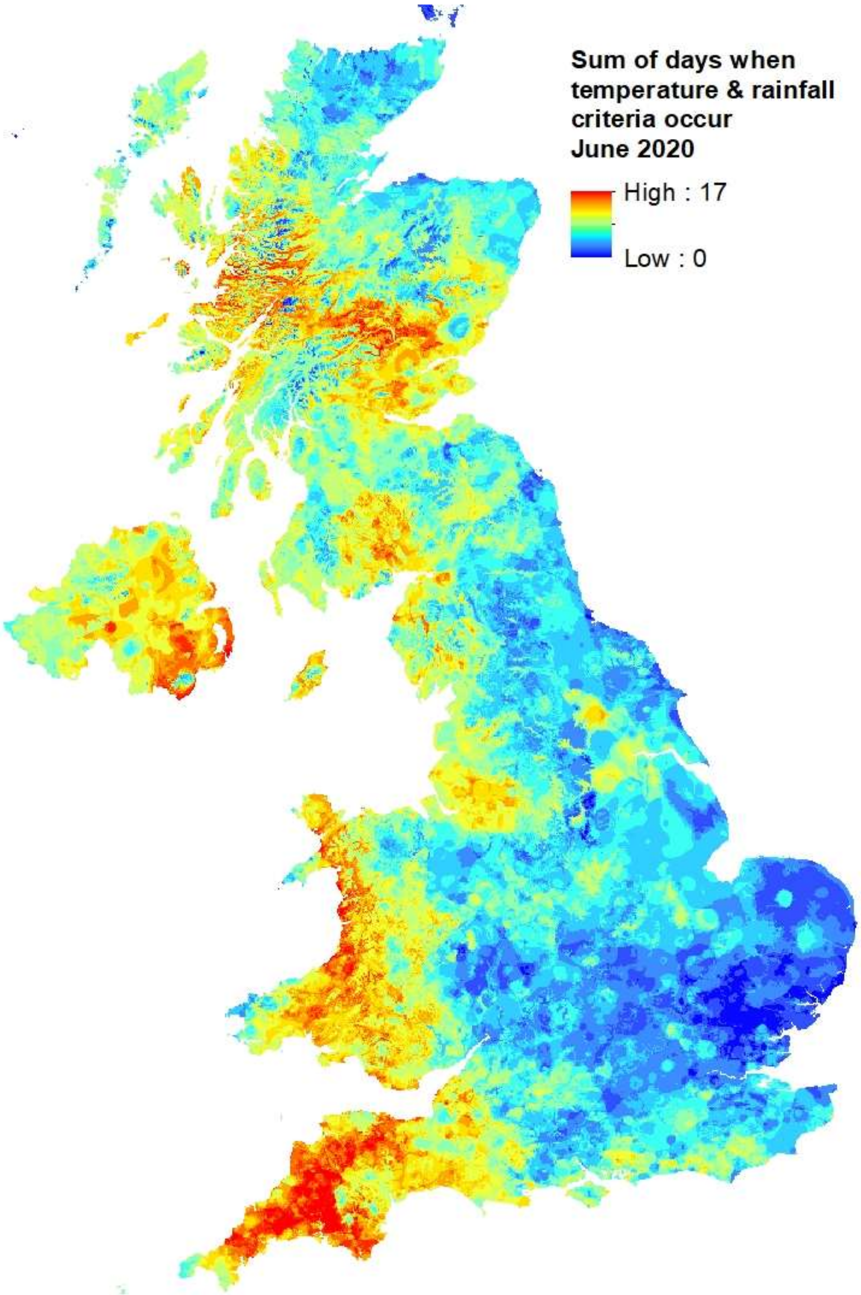
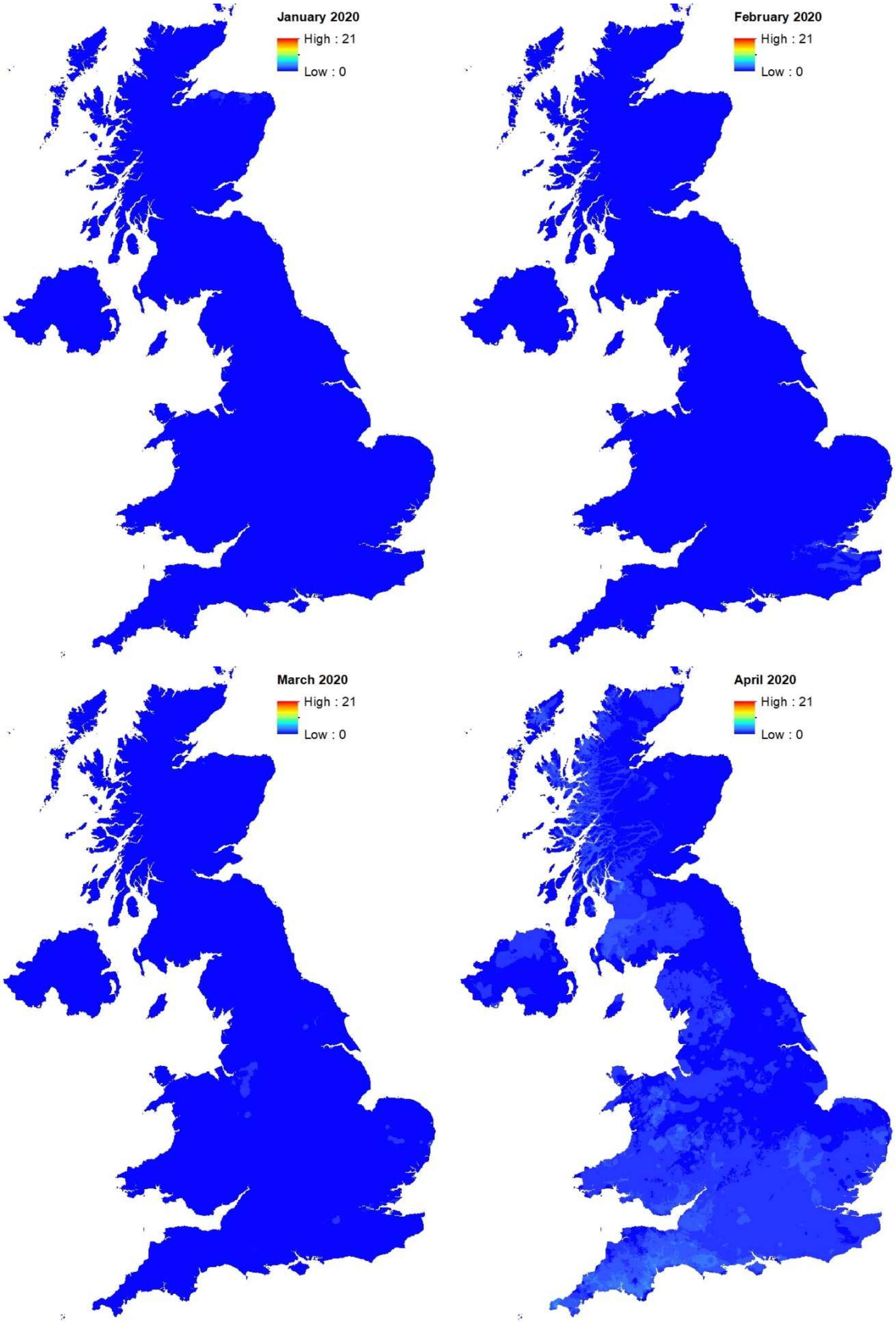
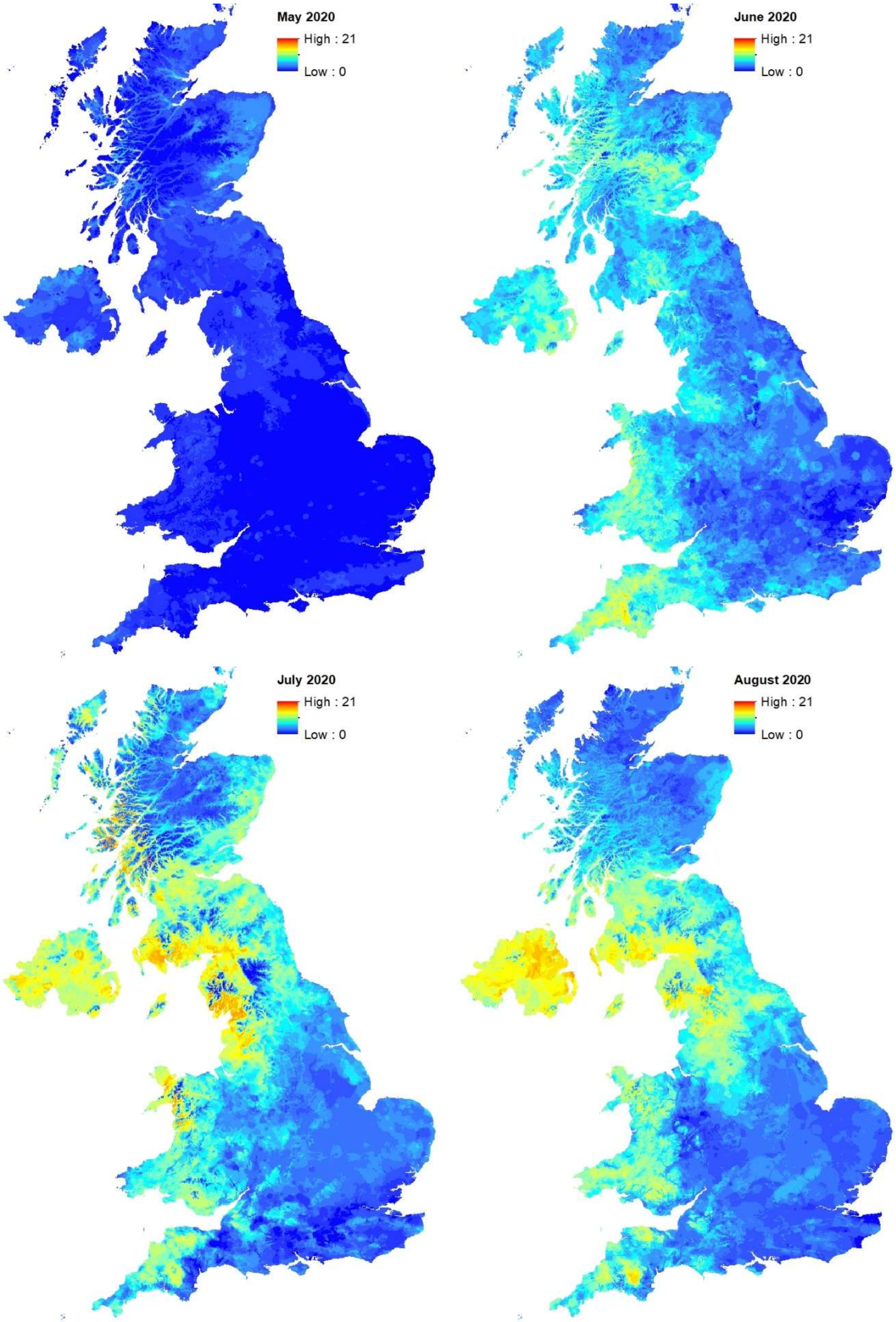


Figure 3. Sum of grid cells meeting the combined criteria for *Phytophthora pluvialis* in June 2020.

Figure 4 is an illustration of how the summed risk values vary for each month throughout a year, 2020 as an example.




May 2020
High : 21
Low : 0
June 2020
High : 21
Low : 0
July 2020
High : 21
Low : 0
August 2020
High : 21
Low : 0

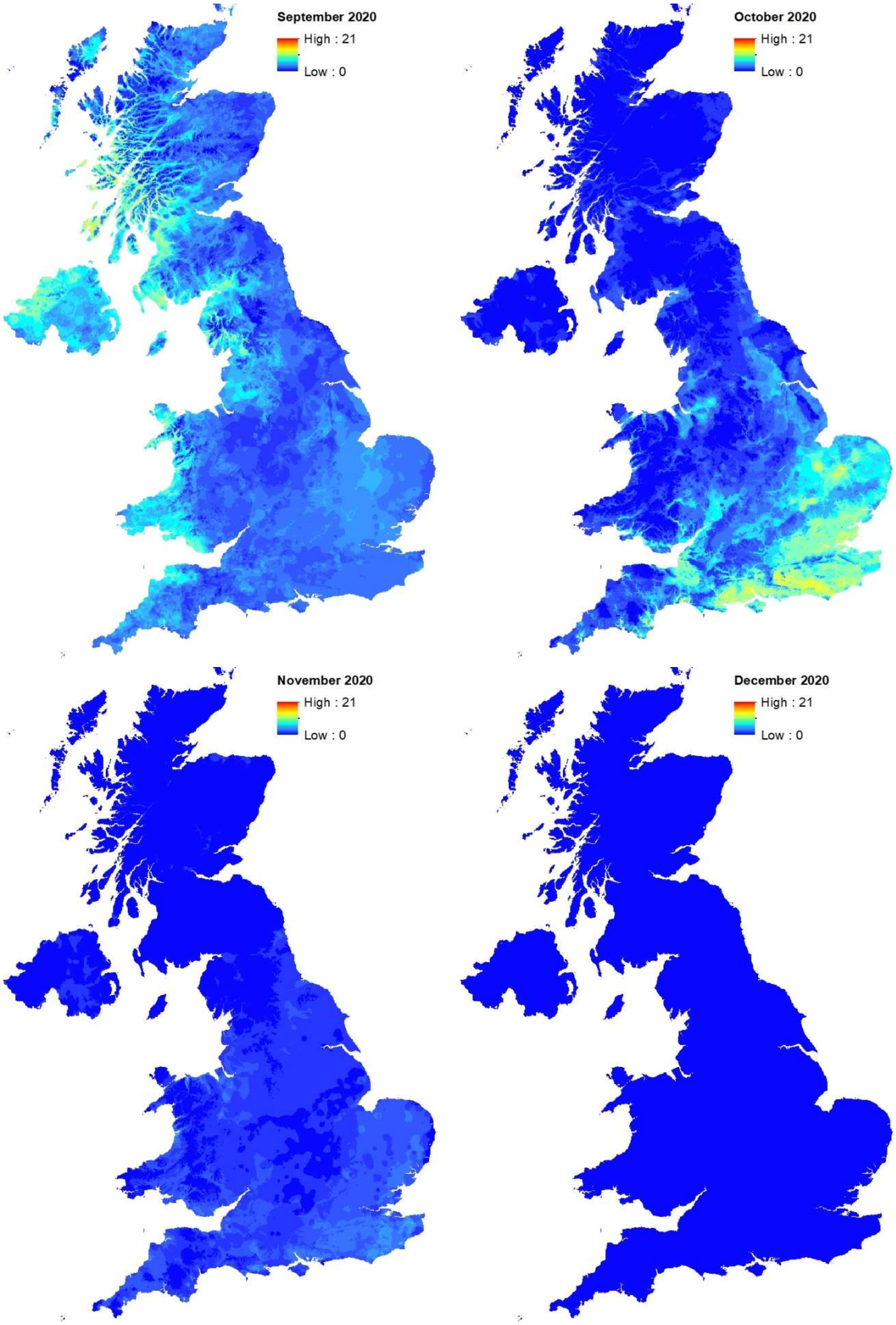


Figure 4 - Series of monthly summed risk days for 2020.

2.4. Application of a disease risk index for *Phytophthora ramorum*

Applying the risk index for *P. ramorum* was a more involved process, the main reason being that the HadUK-GRID data grids do not include a daily average product for RH but rather a monthly average (Figure 5). Furthermore, the equation that defines the response surface, based on Tooley *et al*. (2009), uses a duration of high humidity per day rather than an average daily value (Figure 6).

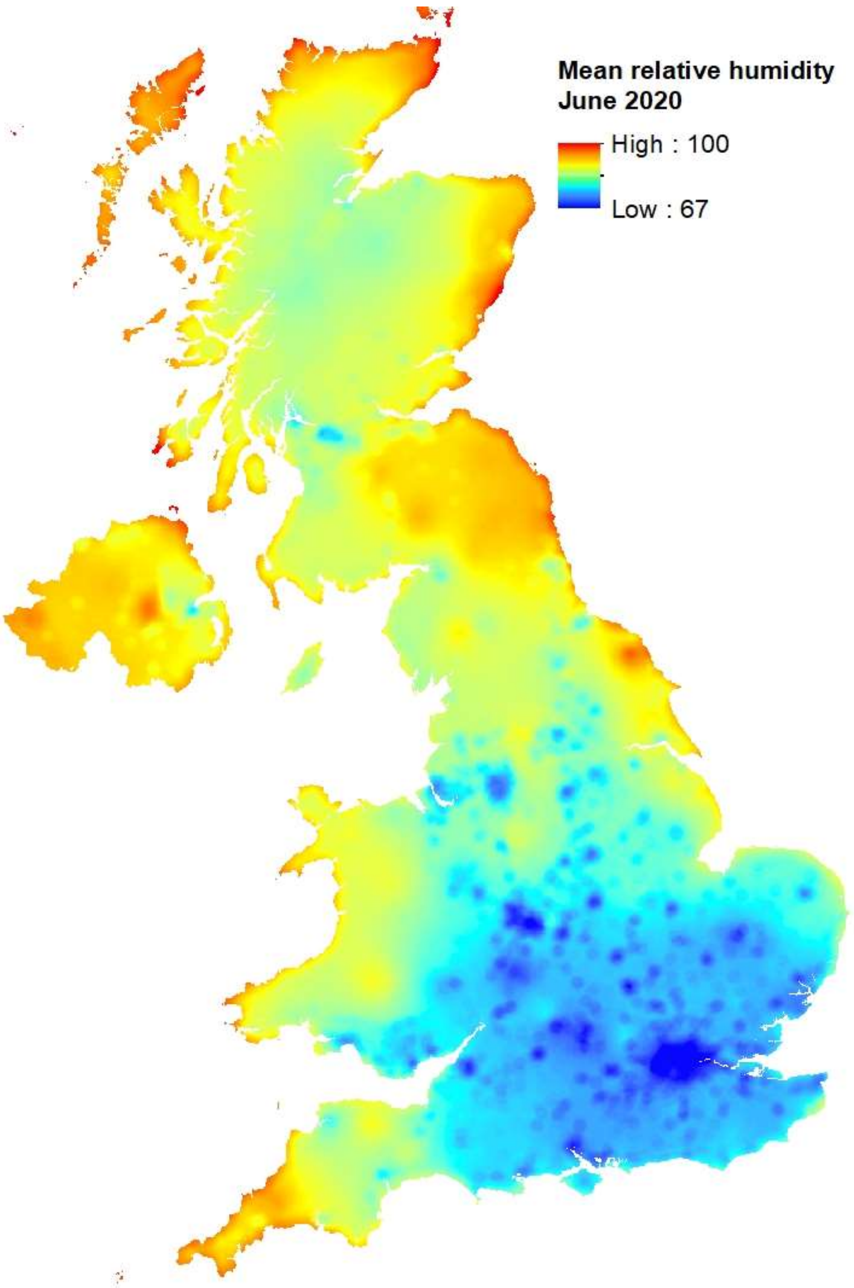


Figure 5. Mean relative humidity (%) for an example month, June 2020.

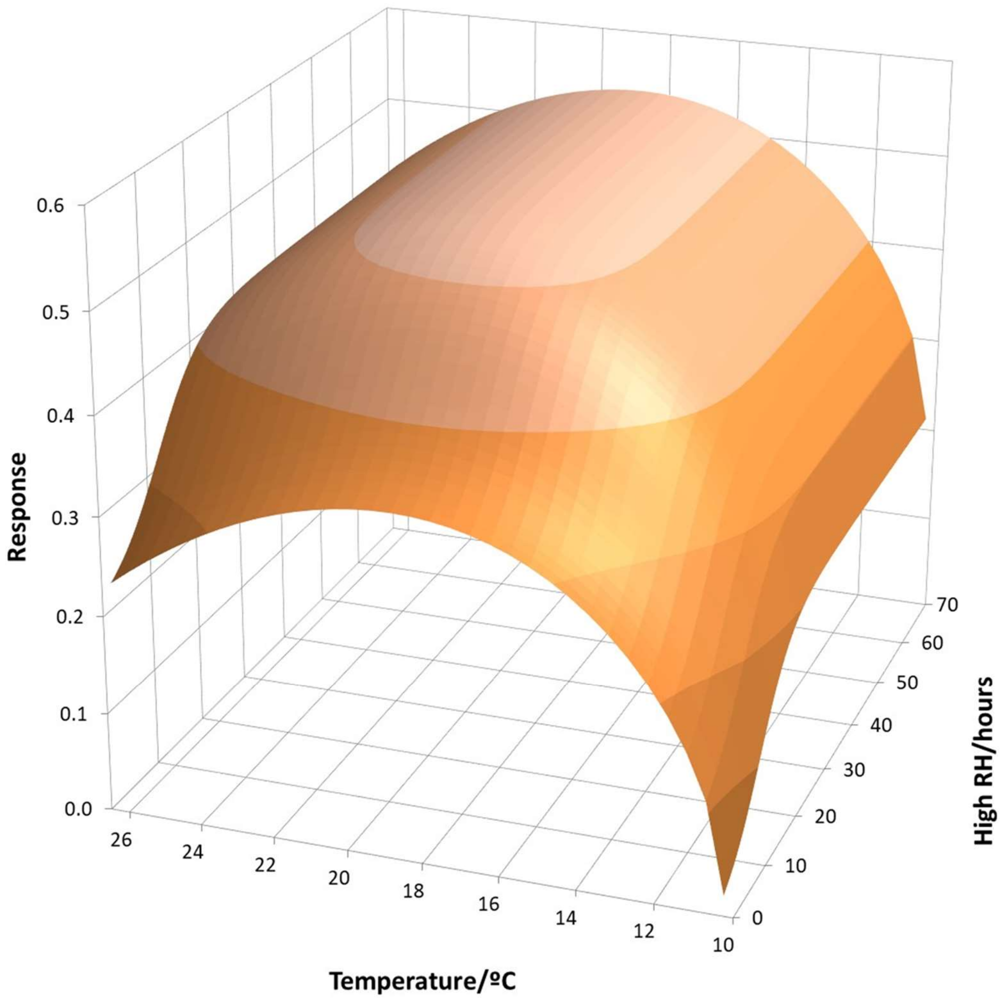


Figure 6. Response surface for risk of infection by *Phytophthora ramorum* based on Tooley *et al*. (2009). An Excel compatible version of the equation that defines the surface is **y = 0.212 / (1 + 9.11 * (EXP (-0.21 * rh_dur))) + (0.01 * (((temp - 10) ^ 0.602) * ((31 - temp) ^ 0.868))), where 'temp' is daily maximum temperature and 'rh_dur' is number of hours with relative humidity >= 90%.**

A potential solution to transform the monthly RH values to duration was attempted using a different source of weather data, hourly site-specific observations from the UKMO's DataPoint service (https://www.metoffice.gov.uk/services/data/datapoint/uk-hourly-site-specific-observations). This comprises up to 10 weather parameters (usefully for this project one of the parameters is hourly RH) from around 130 UK meteorological station locations. Fera Science Ltd. has been accessing the source since May 2015 (Figure 7).

The full annual coverage of 2016 - 2022 and ~130 locations amounted to a total of over 7.9 million hourly readings of RH. The process ran a regression analysis using a calculated daily RH value at each date and location as the response variable and the number of hours that RH on the same date and location were >= 90%. As a further comparison using the location hourly data the correlation between daily mean RH and the number of hours each day when RH was between 80-90%, 70-80%, 60-70%, 50-60% and 40-50% were also calculated to assess whether any relationship was apparent (Table 1).

Table 1. Correlation values between daily mean relative humidity (RH%) and daily counts of hourly relative humidity for six bands, using hourly observation data from 130 UK locations for the period 2016-2022.

	Hourly RH count	>=90%	>= 80% - < 90%	>= 70% - < 80%	>= 60% - < 70%	>= 50% - < 60%	>= 40% - < 50%
Daily mean RH%	1						
>= 90%	0.83	1					
>= 80% - < 90%	0.07	-0.40	1				
>= 70% - < 80%	-0.45	-0.63	0.01	1			
>= 60% - < 70%	-0.65	-0.52	-0.27	0.27	1		
>= 50% - < 60%	-0.67	-0.38	-0.27	-0.01	0.38	1	
>= 40% - < 50%	-0.57	-0.26	-0.21	-0.06	0.12	0.43	1

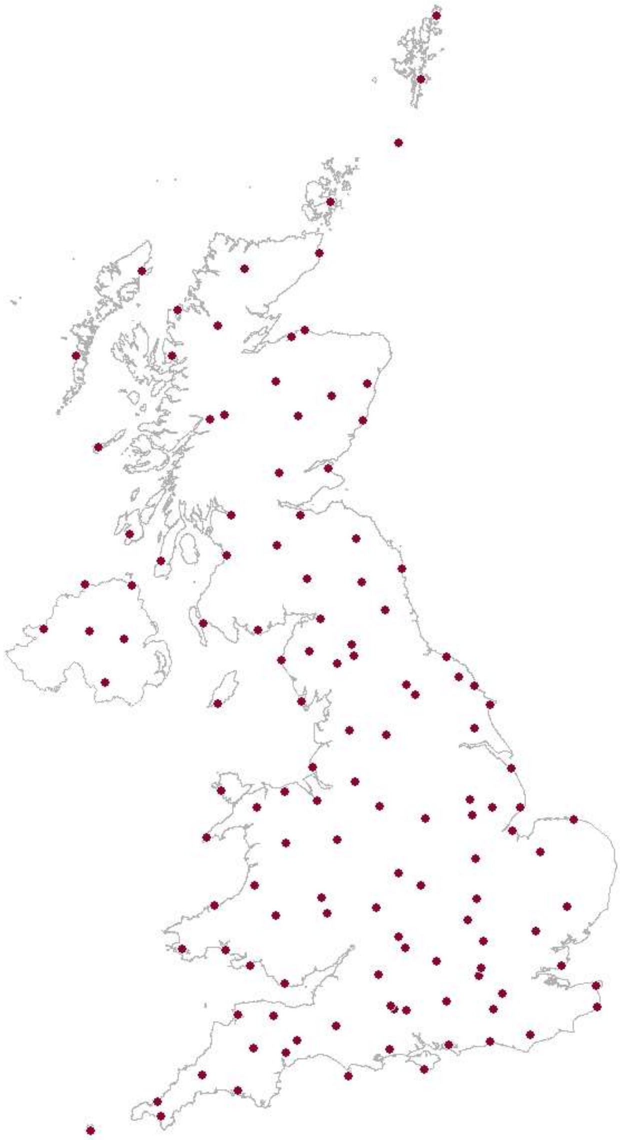


Figure 7. Locations of 130 hourly weather observation stations available from UK Met Office’s DataPoint service.

The daily mean RH values and the daily count of hours >= 90% were averaged for each day within each month across the seven years available before running a cubic regression analysis for each month (Figure 8 is an example for January).

The correlation results indicate a strong relationship between daily mean RH (%) and the number of hours per day >= 90% RH, but a weaker and inverse result for the other counts of daily RH values.

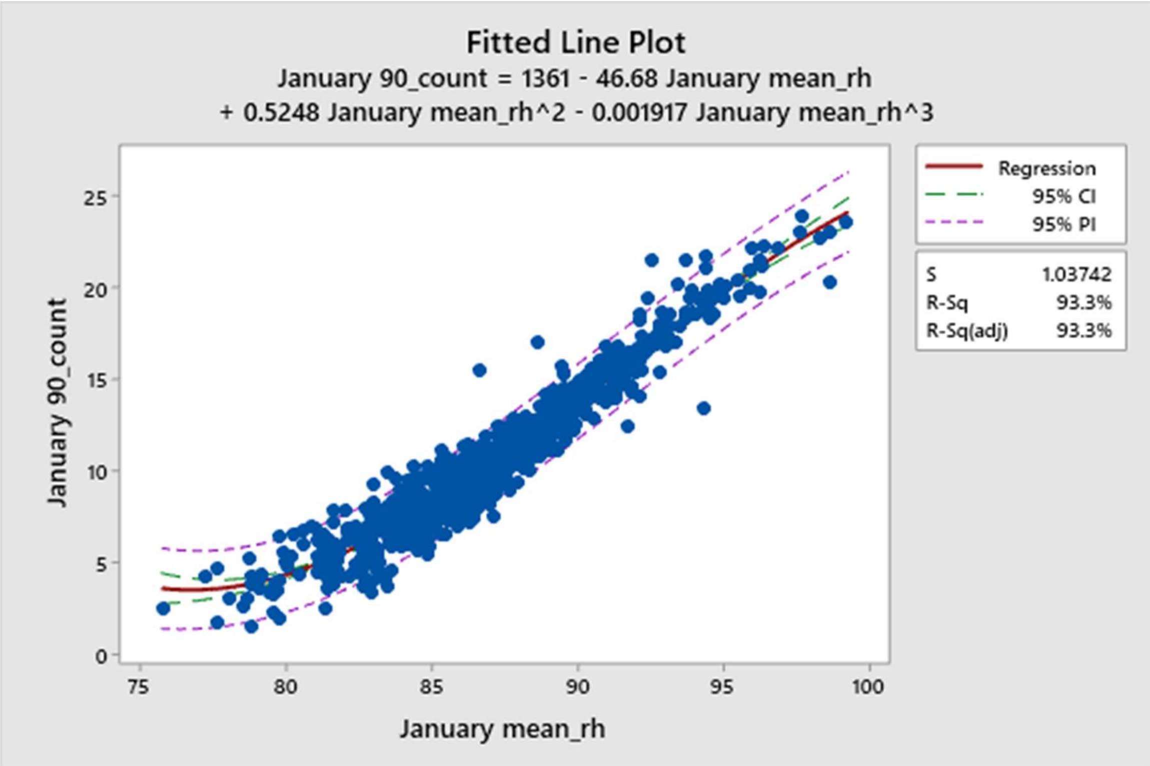


Figure 8. Example of cubic regression plot for month of January, 2016-22. Response variable is the count of number of hours per day >= 90% RH and explanatory variable is daily mean RH (%).

The regression equations for all 12 months across the years available were calculated (Table 2). Taking the monthly mean RH grids as input (372 in total) a further R program was written to apply the relevant regression to the respective month to produce 372 grids transformed into hours duration of RH >= 90% (Figure 9). The R program also duplicated each of the monthly grids to ensure the same number as the daily temperature grids. So, for the example of June 2020 there would be 30 grids of daily RH duration sharing the same values. This simply made it easier to apply the response surface equation (Figure 6) using the R programming language. With the daily input grids for the 31 years the response surface equation was applied to each day (Figure 10) and then also summed for each month. A monthly value was chosen as this was considered by the stakeholders to be the most useful update period (Figure 11).

Table 2. Regression equations for each month based on monthly means of relative humidity (RH) and mean

number of hours per day with RH >= 90%. Years of data are between 2016-2022.

Month	Cubic Regression Equation	R^2-adj
January	Jan_90_count = 1382 - 47.28 * Jan_mean_RH + 0.53 * Jan_mean_RH^2 - 0.0019 * Jan_mean_RH^3	94.4
February	Feb_90_count = 544.6 - 18.86 * Feb_mean_RH + 0.21 * Feb_mean_RH^2 - 0.00074 * Feb_mean_RH^3	88.5
March	Mar_90_count = 258.9 - 8.53 * Mar_mean_RH + 0.087 * Mar_mean_RH^2 - 0.00025 * Mar_mean_RH^3	85.3
April	Apr_90_count = 66.43 - 2.51 * Apr_mean_RH + 0.028 * Apr_mean_RH^2 - 0.00008 * Apr_mean_RH^3	81.7
May	May_90_count = - 113.1 + 4.84 * May_mean_RH - 0.071 * May mean_RH^2 + 0.00036 * May_mean_RH^3	78.6
June	Jun_90_count = - 130.8 + 5.63 * Jun_mean_RH - 0.082 * Jun_mean_RH^2 + 0.00042 * Jun_mean_RH^3	82.9
July	Jul_90_count = - 69.99 + 3.26 * Jul_mean_RH - 0.052 * Jul_mean_RH^2 + 0.00029 * July mean_RH^3	88.7
August	Aug_90_count = - 137.6 + 6.29 * Aug_mean_RH - 0.095 * Aug_mean_RH^2 + 0.00049 * Aug_mean_RH^3	87.9
September	Sep_90_count = 302.3 - 10.07 * Sep_mean_RH + 0.106 * Sep_mean_RH^2 - 0.00033 * Sep_mean_RH^3	88.4
October	Oct_90_count = 1020 - 35.70 * Oct_mean_RH + 0.409 * Oct_mean_RH^2 - 0.0015 * Oct_mean_RH^3	91.8
November	Nov_90_count = 2128 - 73.28 * Nov_mean_RH + 0.832 * Nov_mean_RH^2 - 0.0031 * Nov_mean_RH^3	94.4
December	Dec_90_count = 1919 - 65.65 * Dec_mean_RH + 0.739 * Dec_mean_RH^2 - 0.0027 * Dec_mean_RH^3	93.3

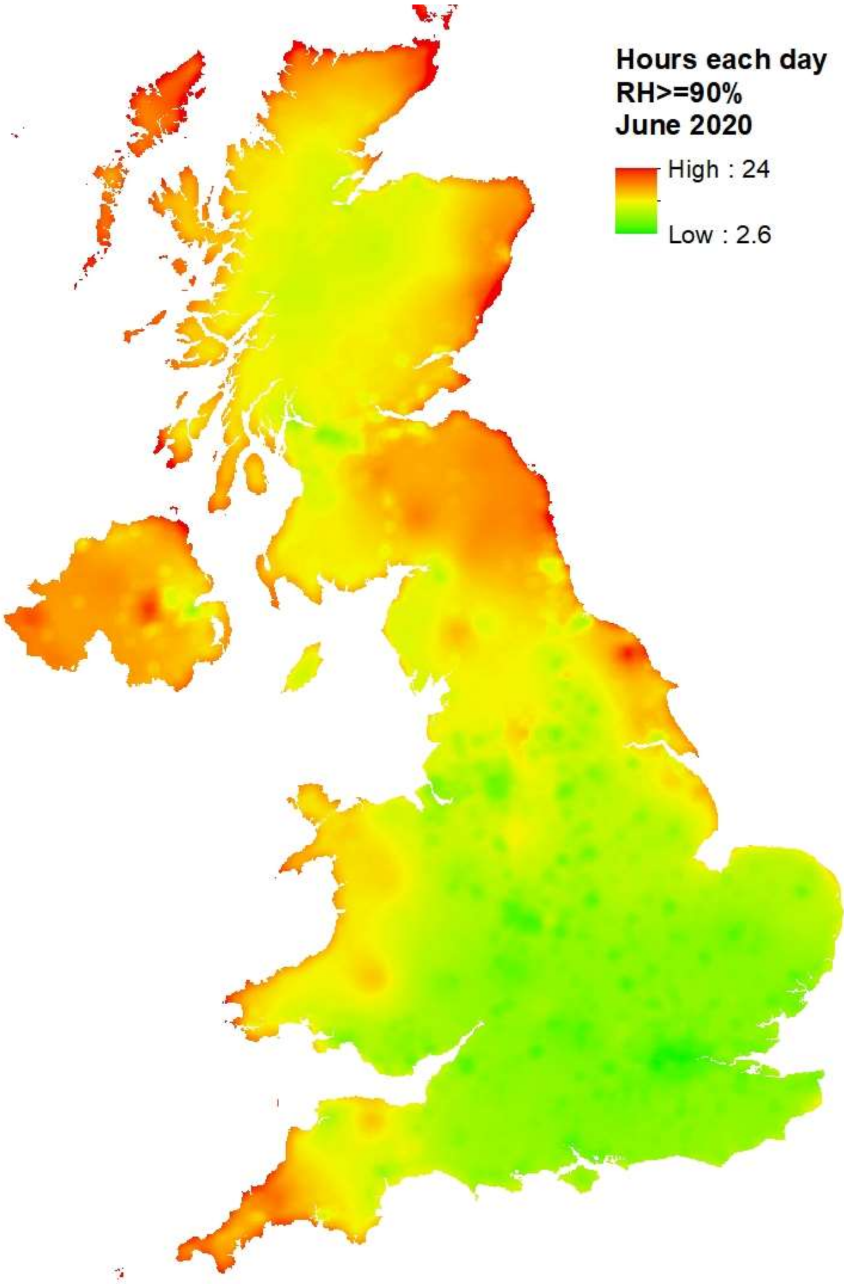


Figure 9. Example of a month (June 2020) transformed by regression from monthly mean relative humidity (RH) to mean number of hours per day with RH >= 90%. Each monthly grid was replicated to produce an estimate of daily RH duration values for the 1991-2021 period.

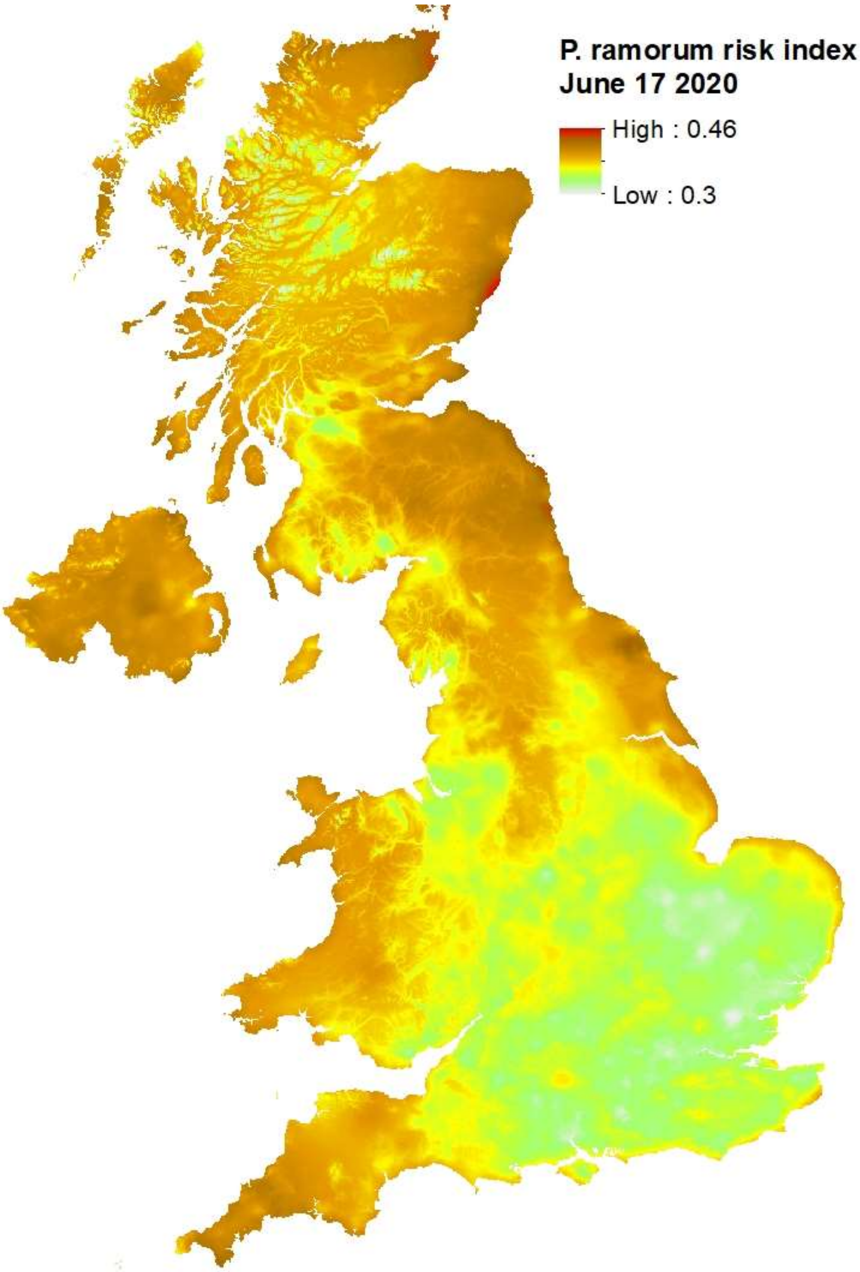


Figure 10. Daily risk index for *Phytophthora ramorum* based on the surface response model of Tooley *et al*. (2009) and the Met Office Hadley Centre 1km gridded weather data (HadUK-GRID) for an illustrative day, 17th June 2020.

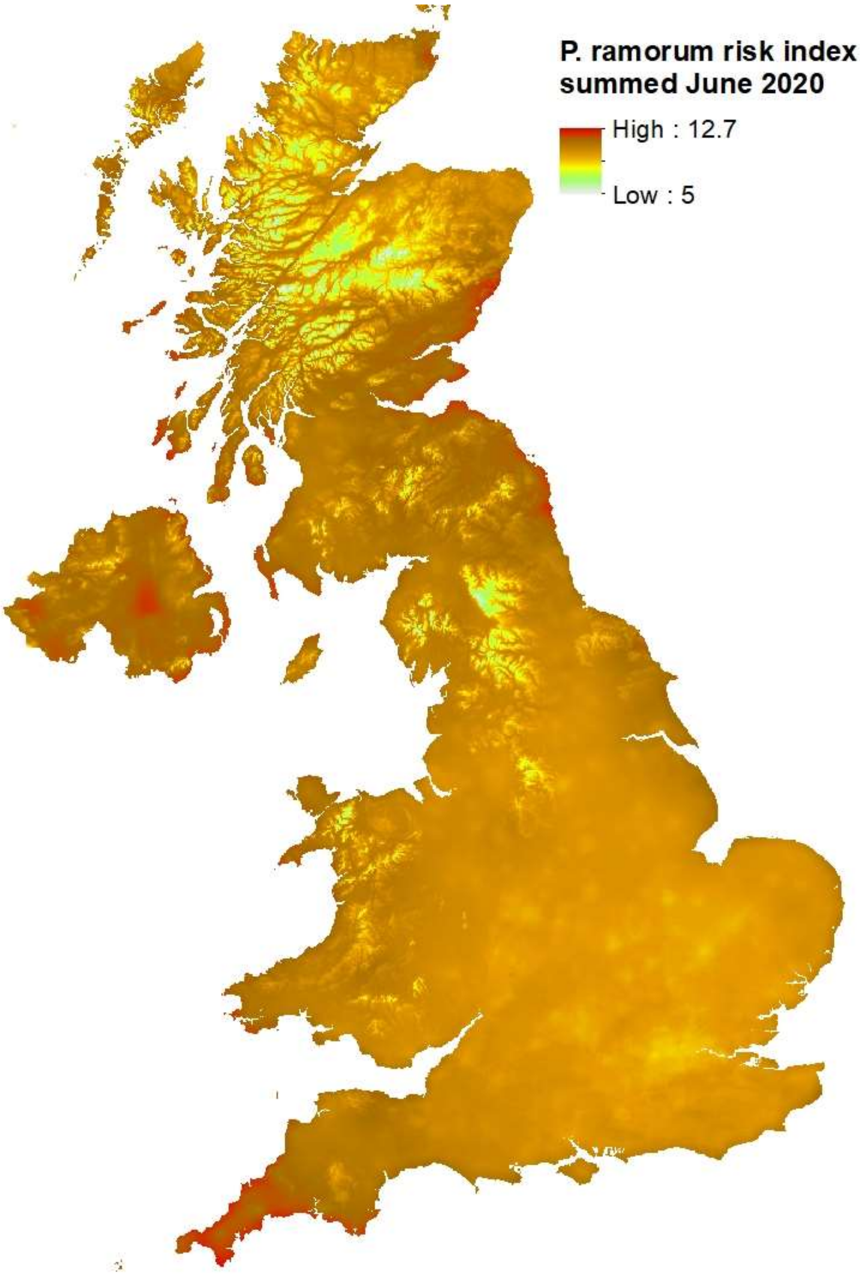


Figure 11. Monthly risk index for *Phytophthora ramorum* summed from the daily results (e.g., Figure 10), illustrated for the month of June 2020.

3. *Phytophthora* climate risk web tool

An interactive web tool titled '*Phytophthora* climate risk tool' has been developed (see link: https://hadleyserver.metoffice.gov.uk/Phytophthora/) to enable users to explore and download the UK risk indexes (and underlying data) for *P. ramorum* and *P. pluvialis* (as detailed above) for each year between 1991 and 2021. Further years would be relatively straightforward to include if required. As well as providing UK-wide maps of estimated *P. ramorum* and *P. pluvialis* risk indexes (at 1km grid resolution), the web tool also enables users to explore variations in the indexes for each region of the UK as time series from 1991 to 2021 and compare these with daily variations in climate (temperature and precipitation) for the same regions. Individual 1km grid points can also be selected on each map and compared with the monthly average index for each month of the selected year. Further details on the scope and functionality of the ***Phytophthora* climate risk tool** are available *via* information buttons on the tool. Future updates to the web tool, including the addition of more years, should be relatively straightforward.

4. Discussion and options for further development

This report and the associated web tool have been developed to provide easily accessible estimates of the spatial and temporal suitability of climate for *P. ramorum* and *P. pluvialis* across the UK. The indices developed and visualised alongside climate variables (temperature and precipitation) on the web tool can support users in a range of ways, including:

- The mapped risk indices can help users identify locations across the UK at greatest climate-related risk from *P. ramorum* and *P. pluvialis* and understand if the locations most at risk from these pathogens are shifting significantly due to climate variability or remaining relatively constant from year to year.
- Daily changes in climate (temperature and rainfall) can be compared with the number of suitable climate days per month for individual years, providing users with insight on the variability of high-risk climate conditions within and between years.
- The monthly climate suitability information and mapped indices can help users to distinguish the most important time of the year for infection in different parts of the UK. For example, for most years and regions July is the most climatically suitable time of year for both *P. ramorum* and *P. pluvialis*, a wet July could therefore provide an early warning of relatively high *Phytophthora* risk. Such information could be used to inform surveillance and other management plans.
- The graph of number of suitable days per month for different regions across the UK can be used to assess if there is a significant trend in suitable days per year or month in different locations. An understanding of current trends could help with long-term planning of woodland planting and management into the future.

Mapped data can be downloaded from the web tool for inclusion into reports and/or layered with other relevant information, e.g. pathogen observation data, for more focused analyses including the addition of multiple indices to understand potential compound risks across the UK.

This project has been designed as a short (~6 month) scoping study to estimate climate suitability indices utilising relatively high resolution (1km) climate data across the UK and demonstrate a bespoke web tool to support users to assess and manage the climate-related risks to UK trees and ecosystems. There are many ways in which this work could be improved and progressed, some of which are listed below:

- While the indices for *P. pluvialis* suitability are novel for the UK, several other studies have estimated risk indices for *P. ramorum* (see Introduction), and it would be important to compare the different methods and estimates to understand the nature of differences between them.

- Surveillance and other observation data could be included directly on the web tool showing how the climate suitability indices compare with locations where the pathogens have already been observed.
- More *Phytophthora* species could be included on the web tool, provided a suitable index is available. Also, functionality could be added to enable assessment of compound risks from multiple species.
- Other layers of relevant information could also be added to the web tool, such as location and connectivity of vulnerable plant species and ecosystems.
- For specific locations and high-risk areas it would be possible to provide higher resolution spatial detail on topographic variations or microclimate (utilising a very high-resolution microclimate model, such as detailed in Maclean *et al*., 2021).
- Future climate change scenarios could also be utilised to assess potential future changes in the risk estimates across the UK.

Further developments to the methodologies and web tool would need to be conducted in collaboration with a wide range of Plant Health and particularly *Phytophthora* experts and co-designed with the organisations and individuals who are responsible for managing *Phytophthora* risks to ensure robust scientific estimates of risk are provided in a way that is most useful and useable by the end users.

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