Predicting facial eczema risks in a changing New Zealand climate

Craig B. PHILLIPS[1]*, Patricia L. JOHNSON[2], Federico TOMASETTO[1], Kathryn MCRAE[2], Tony VAN DER WEERDEN[2]

[1]*AgResearch, Lincoln Research Centre, Private Bag 4749, Christchurch*
[2]*AgResearch, Invermay Research Centre, Private Bag 50034 Mosgiel*
*Corresponding author: craig.phillips@agresearch.co.nz

Abstract

Facial eczema is a major concern for New Zealand farmers due to its economic impact and animal welfare implications. The disease occurs when animals ingest sporidesmin, a mycotoxin produced by spores of the fungus *Pseudopithomyces chartarum*. Spore production is related to weather conditions; thus the incidence and severity of facial eczema varies between years, with the disease commonly occurring from late summer through autumn in the North Island. We developed a simple model to estimate climatic suitability for *P. chartarum* sporulation and ran it using climate data for 2008-2021 to compare its estimates with spore counts from the same years. Model climatic suitability estimates had significant linear correlations with an index of exposure to spores derived from spore counts at both national and local scales. Model results were also consistent with a documented outbreak of facial eczema. Using predicted future climate data from the Hadley Centre Global Environment Model version 2 and two emissions scenarios, the model suggested climatic suitability for *P. chartarum* sporulation will increase with time in many New Zealand regions, particularly in the southern North Island and eastern parts of the South Island. However, it could remain relatively static in some other areas, thus the degree of change in climatic suitability for *P. chartarum* sporulation is predicted to vary between New Zealand regions.

Keywords: *Pseudopithomyces chartarum*, climate change, model, animal health

Introduction

Facial eczema is a major concern for New Zealand farmers due to its economic impact and animal welfare implications. The disease occurs when animals ingest sporidesmin, a mycotoxin produced by spores of the fungus *Pseudopithomyces chartarum*. Early reports of animal deaths due to facial eczema date back to the late 1800s (Gilruth 1908), but the link between the disease and *P. chartarum* was only established in 1958 (Percival and Thornton 1958). Although the fungus occurs in other countries (Collin et al. 1998; Dijkstra et al. 2022; Pinto et al. 2005), it is most problematic in the North Island of New Zealand (Di Menna et al. 2009; Cuttance, Mason, and Laven 2021; Lawrence et al. 2022) where, in contrast to other locations including the South Island, high proportions of *P. chartarum* isolates have the ability to produce sporidesmin (Collin, Odriozola, and Towers 1998).

The incidence and severity of facial eczema varies between years, with the disease commonly occurring from late summer through autumn in the North Island. *Pseudopithomyces chartarum* sporulates most actively at grass minimum temperatures above 12 °C (Mitchell et al. 1959), with 24 °C being the most active temperature in vitro (Brook 1963). It requires moisture for sporulation (Mitchell et al. 1959; Brook 1963), with heavy or continuing rainfall reducing its occurrence (Mitchell et al. 1959). It has been suggested that climate change may increase the distribution and abundance of *P. chartarum* both in New Zealand (Di Menna et al. 2009; Dennis et al. 2014; McRae et al. 2018) and western Europe (Dijkstra, et al. 2022). Our study aimed to improve upon previous evaluations of the potential effects of climate change on facial eczema in New Zealand by developing a simple model of *P. chartarum*'s temperature and rainfall requirements for sporulation, comparing its results to historical spore count data, then using it to predict how the prevalence of high spore counts—and by implication facial eczema—may change in the future.

Materials and Methods

Data processing

All data processing, modelling and graphing was conducted using R version 4.2.3 (R Core Team 2023) and functions from packages including the tidyverse (Wickham et al. 2019), sf (Pebesma 2023), officedown (Gohel and Ross 2023), officer (Gohel 2023) and flextable (Gohel and Skintzos 2023).

Historical climate data

Historical climate data were NIWA's Virtual Climate Station Network (VCSN) data (NIWA 2022) comprising daily rainfall and maximum and minimum air temperatures for 1972-2021 on a regular 0.05° grid (~5 km) of 11491 locations spanning the North, South and Stewart Islands. The data were filtered to the years useful for evaluating the model (see below), summarised to weekly means and filtered to the first 16 weeks of each year before being used to model climatic

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suitability for *P. chartarum* sporulation.

Model of climatic suitability for *P. chartarum* sporulation

The model calculates an index of climatic suitability for *P. chartarum* sporulation that has range 0-1 (low-high). The suitability index is the product of a temperature index (range 0-1) and a rainfall index (range 0-1).

Temperature Index

Mitchell et al. (1959) recorded significant sporulation of *P. chartarum* as grass temperature increased above 12 °C, whereas Smith et al. (1965) considered 12.8 °C to be the minimum threshold for sporulation. VCSN data do not include grass minimum temperature (NIWA 2022) so we sought a way to use air temperature instead.

The climatic factors that most strongly influence the relationship between air temperature and grass minimum temperature are cloud cover, windspeed and topography (Bootsma 1976), but VCSN data do not include cloud cover (NIWA 2022). Moreover, attempts to correlate air temperature with grass minimum temperature in hilly terrain were unsuccessful (Bootsma 1976). Rather than attempting to convert air temperatures to grass minimum temperatures throughout New Zealand, we conducted a sensitivity analysis to find the minimum air temperature that gave the highest correlations between model estimates of climatic suitability for *P. chartarum* sporulation and our validation metrics (see below). Grass minimum temperature is usually lower than or similar to air temperature (Bootsma 1976), thus we evaluated air temperatures ranging from 12 to 17 °C in increments of 0.5 °C. For each validation metric, we ranked the correlations obtained using different temperatures from high to low and chose the temperature that gave the lowest sum of ranks, which was 14 °C (data not shown).

The model assumed zero sporulation above a maximum air temperature of 35 °C because Brook (1963) observed declining *in vitro* sporulation of *P. chartarum* above 32 °C and Le Bars et al. (1990) considered 35 °C to be the maximum for *in vitro* colony growth.

The temperature index (t) at location (i) was calculated as the overlap between the observed weekly minimum-maximum temperature range in degrees Celcius (r) at location i and the range 14 to 35 °C ($r_{14,35}$) divided by the observed temperature range (r_i): $t_i = (r_i \cap r_{14,35}) / r_i$.

Rainfall Index

Brook (1963) recorded high *P. chartarum* sporulation with 5.1 to 12.7 mm total rainfall over 1 to 3 days, and Smith et al. (1965) recorded high sporulation with 16.3 to 23.4 mm of rain over 3 to 4 days. Mitchell et al. (1959) suggested *P. chartarum* sporulated when rain fell two or more times per week provided it was not prolonged or heavy, and Smith et al. (1965) proposed that *P. chartarum* spores become less toxic with high rainfall because they become saturated and sporidesmin is water soluble. We interpreted these observations as an optimum rainfall range for sporulation of 5 to 35 mm per week, or an average of 0.7 to 5 mm per day.

The rainfall index increased linearly from zero when a location had 0 mm rain per day to one when it had rain in the range 0.7 to 5 mm per day, declined linearly from one to zero through the range 5 to 7 mm per day, then remained zero with rain greater than 7 mm per day. Let r be the rainfall index and x be rainfall (mm/day) at location i, then r_{xi} =

- $\frac{1}{0.7}x_i$, if $0 \leq x_i \leq 0.7$
- 1, if $0.7 < x_i \leq 5$
- $1 - \frac{1}{2}(x_i - 5)$, if $5 < x_i \leq 7$
- 0, if $x_i > 7$

Suitability Index

Brook (1963) concluded that optimum sporulation conditions occurred when optimum rainfall and temperatures were concurrently observed. Thus, climatic suitability, s, for *P. chartarum* sporulation at location, i, was calculated as the product of the temperature index, t, and rainfall index, r: $s_i = t_i r_i$.

The VCSN data were used to calculate a suitability index for each week (n = 16) of each location (n = 11491) of each year (n = 14), then summarised as the mean of the 16 suitability indices per location to provide a single climatic suitability estimate per location per year. (In an earlier version of the model, we evaluated if at each location the maximum number of successive weeks when the suitability index exceeded various thresholds was more closely correlated with our evaluation metrics than the mean, but it was not.)

Model evaluation

When beginning this research, we expected to find published or unpublished *P. chartarum* spore counts with details of sampling methods, locations, dates, and perhaps observations of sporidesmin toxicity in livestock that could be used for model development and validation. However, despite extensive searching and discussions with other industry participants and researchers we failed to find such spatially explicit records, thus we adopted the more general and less satisfactory approaches to model evaluation described below.

Comparison with Di Menna et al. (2009)

Di Menna et al. (2009) produced maps of New Zealand areas they considered susceptible to facial eczema both in 2009 and in the future under an assumption of 3 °C warming. To check if our model was giving broadly sensible results, its estimates of climatic suitability for *P. chartarum* sporulation were mapped and qualitatively compared with those shown in Figure 1 of Di Menna et al. (2009).

National spore counts

We compiled weekly *P. chartarum* spore counts (spores per 60 g of fresh cut pasture (Gribbles Veterinary 2023) for 2008-2021 that were curated by Gribbles Veterinary. The counts were made by veterinarians and animal health testing companies from pasture samples submitted by farmers for monitoring facial eczema risk to enable timely mitigations (see Cuttanceet al. (2017) and Anexa Veterinary Services (2023) for descriptions of sampling methods). The sampling was heterogeneous in space and time and to ensure farmer privacy Gribbles had aggregated sampling locations to either districts or more recently postcodes (both are hereafter referred to as districts). Gribbles Veterinary informed us that it was technically impossible to trace these aggregated records back to their exact geographic locations. Data from 2008 to 2015 were extracted from saved copies of weekly Gribbles Veterinary reports, and data for 2016 to 2021 were obtained as spreadsheets from Gribbles Veterinary. The format of the reports changed with time and the only value that could be obtained for every year was the highest weekly spore count per district per week. That the spore counts had been aggregated to districts minimised their potential for evaluating spatial variation in model predictions which were at a much finer 5 km resolution. Instead, the spore counts and model estimates of climatic suitability for *P. chartarum* sporulation were compared by summarising them both to single annual values for the years 2008-2021.

Summarising spore counts

Spore counts were filtered to the first 16 weeks of each year to correspond with the model results then used to calculate an annual index of exposure to *P. chartarum* spores. The exposure index, *e*, was calculated as the product of the annual mean spore count, *m*, the proportion of annual spore counts >30000, *p*, and the annual number of districts with spore counts >30000, *d*. Counts of ≥30000 spores/ 60 g pasture are generally regarded as a threshold for implementing facial eczema mitigations (Anexa Veterinary Services 2023). Variable *m* estimated the level of exposure to *P. chartarum* spores, *p* the duration, and the *d* spatial extent. Each variable was normalised to range 0-1 before calculating *e* for year *j* as $e_j = m_j p_j d_j$.

Summarising climatic suitability

To summarise suitability indices derived from the model at a national scale, mean suitability indices for each year (n = 11491) were filtered to locations coinciding with improved pasture (n = 7955) as specified in New Zealand Land Cover Database version 5.0 (Manaaki Whenua Landcare Research 2019) then summarised to a single annual value by calculating the mean.

Comparing spore counts and climatic suitability

The relationship between model estimates of annual suitability for *P. chartarum* sporulation and estimates of annual exposure to spores derived from spore counts was examined by linear regression with exposure as the dependent variable. Our purpose was neither to find the best regression model nor to comprehensively describe the relationship. Rather, it was simply to evaluate if model climatic suitability values increased with exposure to *P. chartarum* spores.

Spore counts and climatic suitability were also compared at three locations near Hamilton. The locations were identified by author PJ who made educated guesses about the locations where spores had been sampled in Gribbles Veterinary's Hamilton district. Annual mean suitability was calculated for each location, and exposure to *P. chartarum* spores was estimated as the annual mean spore count in the Hamilton district multiplied by the proportion of annual spore counts >30000 in the Hamilton district. The Hamilton district had the benefit that it was relatively homogeneous climatically, thus suitability indices exhibited relatively little variation between locations (data not shown). The relationship between annual mean suitability and annual exposure for each location was examined by linear regression with exposure as the dependent variable.

Model predictions for a year and location where facial eczema occurred

Facial eczema in sheep at a farm near Palmerston North in 2019 was documented by Lawrence et al. (2022), thus we checked if model predictions for the same location and year were consistent with the occurrence of facial eczema.

Predictions under future climates

Climate change projections for the period 2030 to 2120 (Mullan, Sood, and Stuart 2018) comprising daily rainfall and maximum and minimum air temperatures on a regular 0.05° grid (~5 km) of 11451 New Zealand locations were obtained from NIWA and treated in the same way as previously described for the VCSN data. We used projections from the Hadley Centre

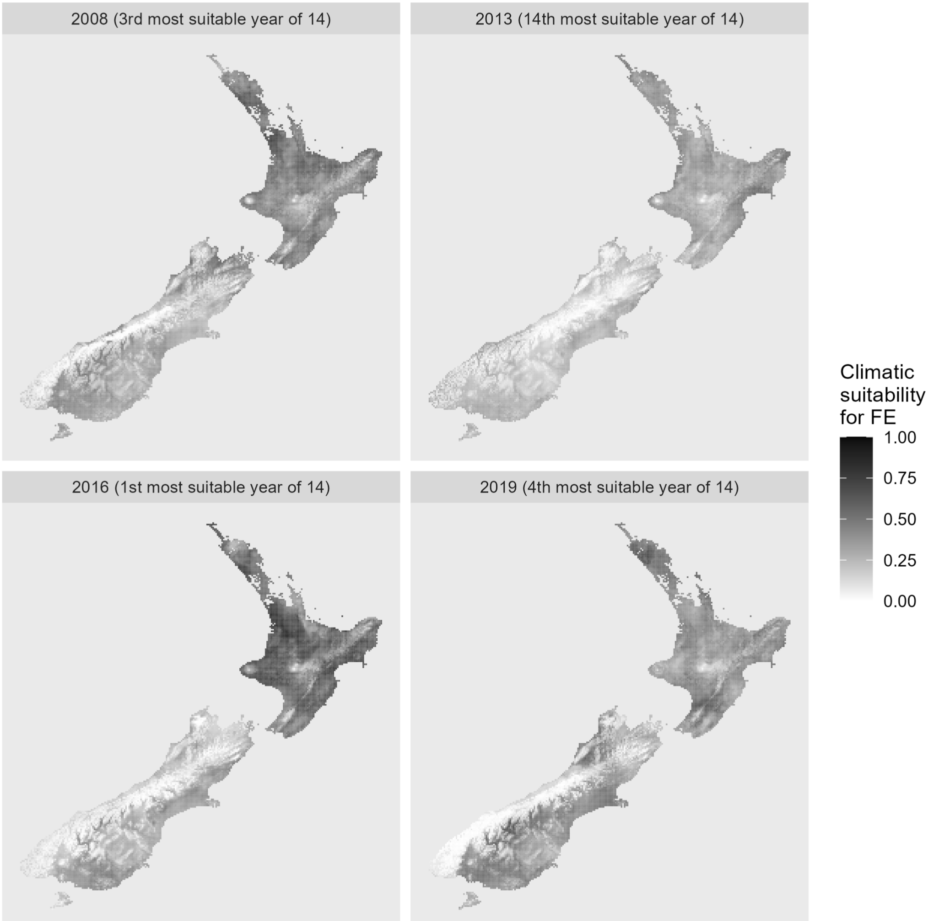

Figure 1 Estimated climatic suitability for *P. chartarum* sporulation in 2008, 2013, 2016 and 2019. Years are ranked by mean of all New Zealand suitability values (n = 11491 per year).

Global Environment Model version 2 (HADGEM2), which is one of six Generalised Circulation Models that NIWA has downscaled to New Zealand (Mullan, Sood, and Stuart 2018). To obtain predictions from both optimistic and pessimistic forecasts of climate change, the model was run using HADGEM2 projections that used Representative Concentration Pathways (RCP) 2.6 (optimistic) and 8.5 (pessimistic).

Results by regional council

A 2020 shapefile of NZ Regional Council boundaries was obtained from Statistics NZ (Statistics New Zealand 2020) and each pasture location (identified as previously described) was assigned to the regional council that it coincided with in the shapefile. Climatic suitability values from the 2008-2021 climate data and the years 2030, 2040, 2050 and 2060 under HADGEM2 RCP 2.6 and HADGEM2 RCP 8.5 were averaged by year and regional council to provide an indication of how the trajectory of predicted change in climatic suitability for *P. chartarum* sporulation varied between NZ regions.

Results

Model evaluation

Comparison with Di Menna et al. (2009)

The New Zealand areas considered susceptible to facial eczema by Di Menna et al. (2009) included Northland, Auckland, Waikato, coastal areas of Taranaki, Bay of Plenty, East Cape, Hawke's Bay and Manawatu-Whanganui, and parts of Wairarapa, Marlborough, Nelson and the West Coast. Model estimates of climatic suitability for *P. chartarum* in 2008, 2013, 2016 and 2019 (Figure 1) were representative of those obtained for other years during 2008-2021 and broadly corresponded with Di Menna et al (2009). Climatic suitability generally declined with both latitude and altitude, though there was variation in this pattern between years. Estimates for 2016, for example, were relatively high for the North Island and low for the South Island compared to 2008 and 2019 (Figure 1).

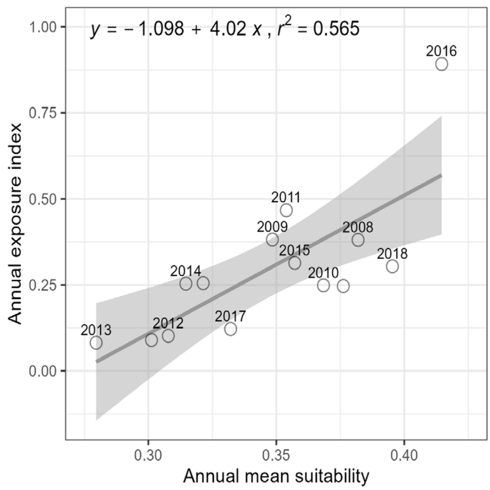

Figure 2 Linear regression of annual exposure index versus annual mean suitability. Shaded area shows 95% confidence interval.

Comparing spore counts and climatic suitability

There was a significant positive linear relationship between annual climatic suitability and estimated annual exposure to *P. chartarum* spores ($R^2 = 0.565$, $F(1, 12) = 15.559$, $p = 0.002$) (Figure 2). The correlation was relatively insensitive to the minimum temperature used when calculating the model's temperature index and ranged from 0.465 at 17 °C to 0.57 at 13 °C. The correlation remained significant when data for 2016—the year with the highest exposure index—was excluded ($R^2 = 0.474$, $F(1, 11) = 9.909$, $p = 0.009$).

For the Hamilton district, the exposure versus suitability regressions (Figure 3) were significant for Hamilton ($R^2 = 0.535$, $F(1, 12) = 13.812$, $p = 0.003$), Horitiu ($R^2 = 0.69$, $F(1, 12) = 26.745$, $p = 0.000$) and Puketaha ($R^2 = 0.671$, $F(1, 12) = 24.527$, $p = 0.000$).

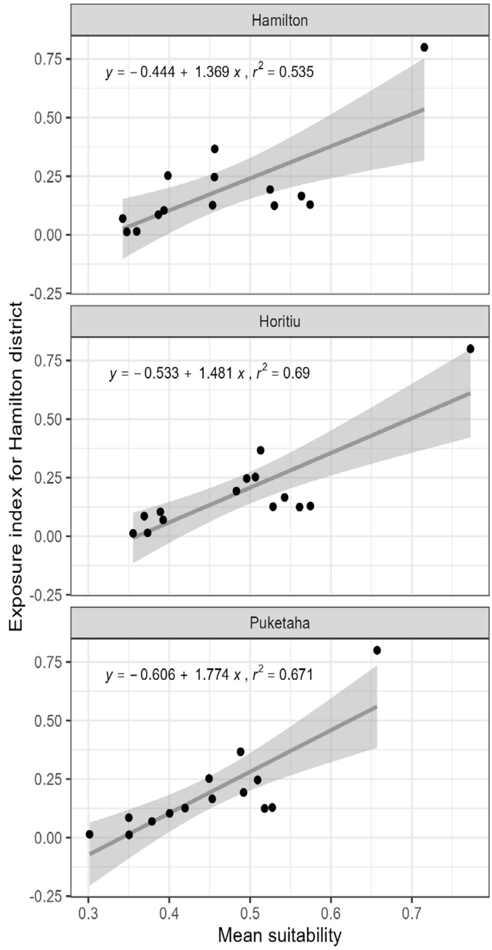

Figure 3 Linear regression of annual exposure index versus annual mean climatic suitability for three locations near Hamilton. Shaded area shows 95% confidence interval.

The correlations were relatively insensitive to the minimum temperature used when calculating the model's temperature index. Their ranges were: Hamilton $R^2 = 0.511$ at 13 °C to 0.566 at 17 °C; Horitiu $R^2 = 0.661$ at 17 °C to 0.726 at 12 °C; and Puketaha $R^2 = 0.647$ at 12.5 °C to 0.684 at both 16 and 16.5 °C.

When data for 2016—the year with the highest exposure index—were excluded, the regression was no longer significant for Hamilton ($R^2 = 0.152$, $F(1, 11) = 1.971$, $p = 0.188$), but remained so at Horitiu ($R^2 = 0.345$, $F(1, 11) = 5.788$, $p = 0.035$) and Puketaha ($R^2 = 0.472$, $F(1, 11) = 9.847$, $p = 0.009$).

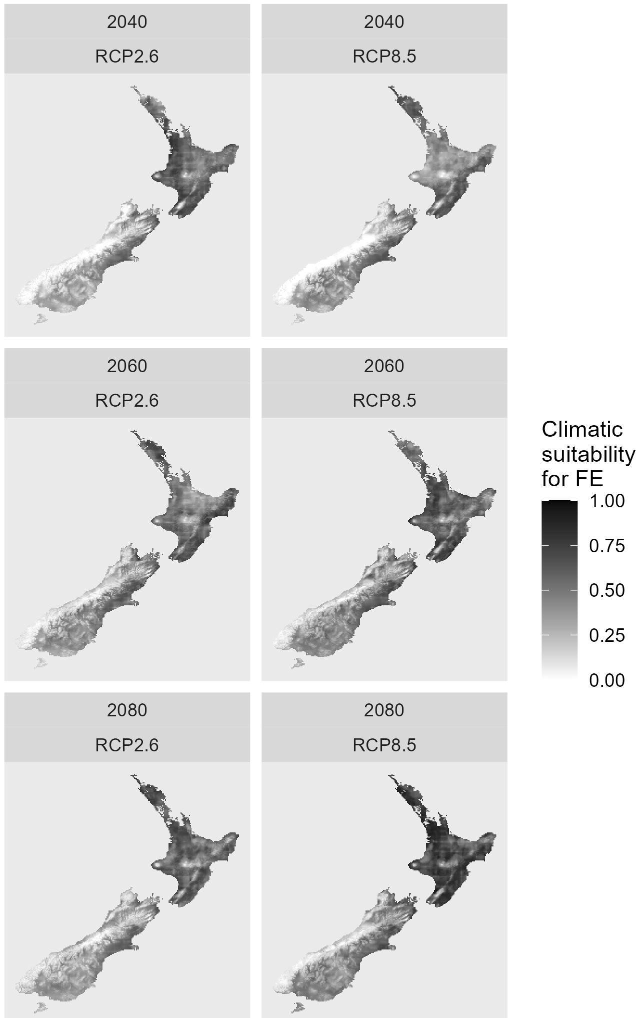

Figure 4 Predicted climatic suitability for facial eczema in 2040, 2060 and 2080 under HADGEM2 emissions scenarios RCP 2.6 and RCP 8.5

Model predictions for a year and location where facial eczema had been recorded

The farm near Palmerston North where Lawrence et al. (2022) documented facial eczema in 2019 had mean suitability in 2019 of 0.611 which was the 86th highest value (top 1.08 %) of all 7955 New Zealand pasture locations (2019 suitability range 0-0.675). The results were relatively insensitive to model minimum temperature for *P. chartarum* sporulation with ranks in 7955 locations ranging from 79th at 13 °C to 198th at 17 °C. Thus, the results suggested that in 2019 the Palmerston North farm was amongst those most suitable for *P. chartarum* sporulation in all New Zealand.

Predictions under future climates

The areas predicted by Di Menna et al. (2009) to become prone to facial eczema if the climate warms by 3 °C included all the North Island except mountainous areas, coastal parts of the South Island except Fiordland and coastal Southland, and parts of inland Otago. Model predictions for the North Island in 2040, 2060 and 2080 corresponded well with Di Menna

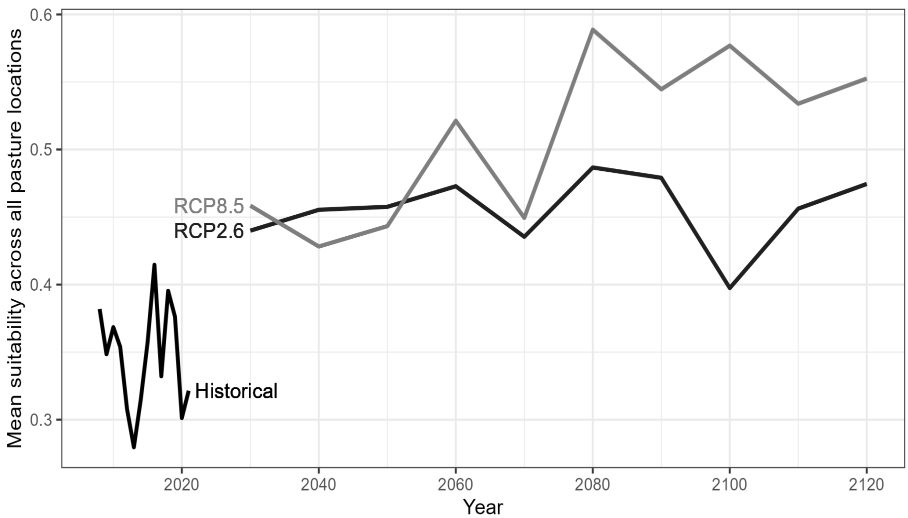

Figure 5 Mean climatic suitability for *Pseudopithomyces chartarum* sporulation for the years 2008 to 2021 (historical) and each decade from 2030 to 2120 using HADGEM2 predictions under emissions scenarios RCP 2.6 and RCP 8.5.

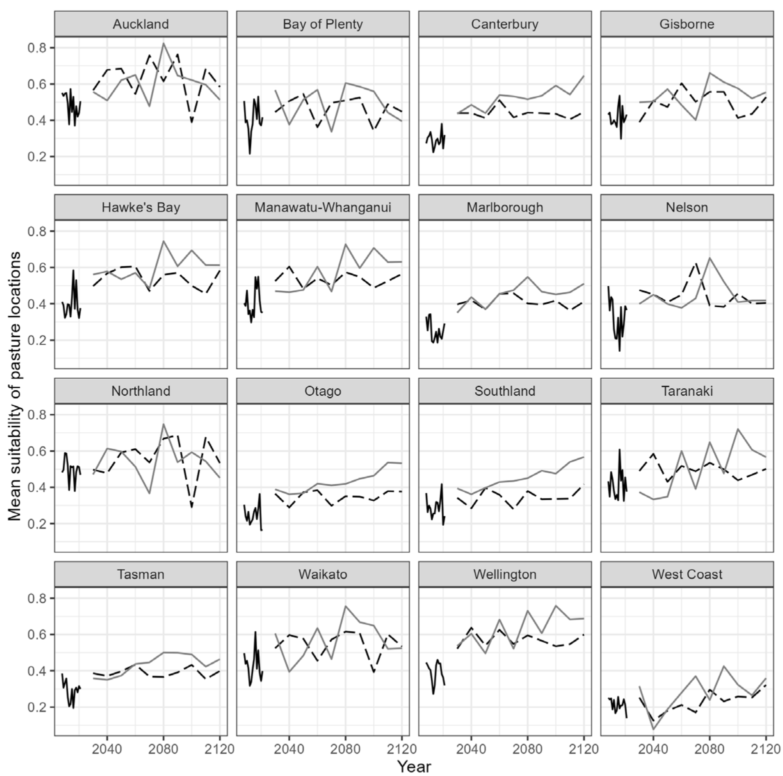

Figure 6 Mean climatic suitability by Regional Council for *Pseudopithomyces chartarum* sporulation for the years 2008 to 2021 (solid black line) and each decade from 2030 to 2120 using HADGEM2 predictions under emissions scenarios RCP 2.6 (dashed black line) and RCP 8.5 (solid grey line).

Table 1 Mean climatic suitability for *Pseudopithomyces chartarum* sporulation by regional council for years 2008 to 2021, and each 10 years from 2030 to 2060 under HADGEM2 RCP 2.6 and RCP 8.5. 'SD' is standard deviation and 'change' is difference between suitability calculated for 2008-2021 and suitability estimate under each future scenario.

	2008-2021		RCP 2.6 2030-2060			RCP 8.5 2030-2060		
Regional Council	Mean	SD	Mean	SD	Change	Mean	SD	Change
Auckland	0.49	0.07	0.62	0.07	0.13	0.58	0.06	0.10
Bay of Plenty	0.41	0.08	0.46	0.08	0.06	0.51	0.09	0.10
Canterbury	0.29	0.04	0.45	0.04	0.16	0.47	0.05	0.18
Gisborne	0.41	0.06	0.49	0.09	0.08	0.51	0.04	0.10
Hawke's Bay	0.40	0.08	0.57	0.05	0.17	0.56	0.02	0.16
Manawatu-Whanganui	0.40	0.08	0.54	0.05	0.13	0.50	0.07	0.10
Marlborough	0.25	0.06	0.41	0.04	0.16	0.40	0.05	0.15
Nelson	0.32	0.10	0.45	0.03	0.12	0.41	0.03	0.08
Northland	0.50	0.06	0.54	0.07	0.05	0.55	0.07	0.05
Otago	0.24	0.06	0.35	0.04	0.11	0.38	0.03	0.14
Southland	0.29	0.06	0.35	0.05	0.06	0.40	0.03	0.11
Taranaki	0.41	0.08	0.51	0.06	0.09	0.41	0.13	0.00
Tasman	0.29	0.06	0.40	0.03	0.11	0.38	0.04	0.09
Waikato	0.43	0.08	0.54	0.06	0.11	0.53	0.11	0.10
Wellington	0.39	0.06	0.58	0.06	0.19	0.58	0.08	0.19
West Coast	0.21	0.04	0.19	0.05	-0.02	0.21	0.11	0.00

et al. (2009) (Figure 4). The main difference between Di Menna et al. (2009) and model predictions for the South Island was the relatively low suitability predicted by our model for much of the West Coast (Figure 4). Between 2040 and 2080, suitability became progressively higher under RCP 8.5 compared to RCP 2.6 (Figures 4 and 5).

At a national level, average climatic suitability for *P. chartarum* sporulation was predicted to increase under both emissions scenarios, with the magnitude of increase greater under RCP 8.5 (Figure 5). Under both scenarios, suitability was predicted to markedly increase between 2021 and 2030. Under RCP 2.6 suitability fluctuated around a roughly constant mean from 2030 to 2120, whereas under RCP 8.5 it continued to increase until about 2080 before stabilising (Figure 5).

Results by regional council

During 2008-2021, the West Coast had least mean suitability for *P. chartarum* sporulation and Northland had most (Table 1). Over the years 2030, 2040, 2050 and 2060 under HADGEM2 RCP 2.6, the West Coast was predicted to have least change in mean suitability for sporulation, Wellington was predicted to have most, and Auckland became the region with highest mean suitability (Table 1; Figure 6). Over the same years under HADGEM2 RCP 8.5, Taranaki and West Coast were predicted to have least change in mean suitability for sporulation, Wellington was predicted to have most, which meant Wellington along with Auckland became the regions with highest mean suitability (Table 1; Figure 6).

Discussion

The data available for model development and testing was limited by the low spatial resolution of the spore count data and sparse documentation of locations and years where facial eczema has been observed. This dictated development of a simple model which, nevertheless, was based on published observations of *P. chartarum*'s response to temperature and rainfall, performed moderately well in the limited evaluations conducted to date, and provided predictions that were broadly consistent with those of previous studies (Dennis et al.; Di Menna et al. 2009). Its predictions were also consistent with Brook (1963) who stated: "The geographical limitation of facial eczema in New Zealand to the North Island and the northern tip of the South Island is evidently a result of the limiting effect of lower South Island summer temperatures on growth of *P. chartarum*". Thus, the general conclusion that over time the climates of many New Zealand regions are likely to become more suitable for *P. chartarum* sporulation is probably robust, whereas details of exactly where and how quickly climatic suitability will increase could be regarded as hypotheses to test by future studies.

That climatic suitability for *P. chartarum* sporulation increased with time in many regions was in part due to the apparent tolerance of the fungus to relatively high temperatures. With the historical climate data used, no New Zealand locations had weekly mean temperatures greater than our assumed upper limit for *P. chartarum* sporulation of 35 °C, thus temperature indices were only low at locations with minimum temperatures below the model threshold of 14 °C, and such locations were expected to become more suitable for *P. chartarum* as the climate warms. Our model predicted that the suitability of the West Coast's climate would increase only marginally with time, whereas Di Menna et al. (2009) – based solely on temperature – predicted that it would markedly increase. This difference was probably due to current expectations that the West Coast will become wetter with time (Mullan et al. 2018), thus exceeding the maximum rainfall of 7 mm per day that our model estimated the fungus will tolerate. This probably also applies to Taranaki where only marginal increases in suitability were predicted under RCP 8.5. However, the difficulty of defining a precise relationship between *P. chartarum* sporulation and the amount and duration of rainfall (Brook 1963; Smith et al. 1965; Mitchell et al. 1959) means there is considerable uncertainty in the model's rainfall index parameters, thus these predictions can only be tentative.

A first step towards improving the model would be to delve more deeply into its results to understand why some years were outliers in linear relationships between annual exposure to spores and climatic suitability. Many factors could reduce the fit between model predictions and spore counts such as: suboptimal model specifications; incomplete knowledge of *P. chartarum* including its interactions with pasture management (Lancashire and Keogh 1968; Lima et al. 2012; Smith et al. 1963); errors inherent in summarising climate data, model results and spore counts; errors in spore count measurements (Cuttance et al. 2017); and variation between VCSN climate data and the real climate (Cichota et al. 2008; Tait et al. 2012; Mason et al. 2017). Other next stage work could include running the model using daily data rather than weekly means, analysing the sensitivity of its predictions to ranges of variable values, and making predictions using future climate data from General Circulation Models additional to HADGEM2. In the longer term, developing a *P. chartarum* population model to estimate spatial and temporal fluctuations in fungus population size could also be useful. However, the value of any of this work will remain arguable until better spore count and facial eczema data are available for testing and developing models. [1]

Our model assumed optimum *P. chartarum* sporulation occurred in temperatures of 14-35 °C. However, *in vitro* experiments indicated appreciable sporidesmin is produced within a narrower range of 20-25 °C (Le Bars et al. 1990), thus in some cases it may be possible for facial eczema risks to remain low even when climatic suitability for sporulation and/or spore counts are high. Similarly, our model predicted that climatic suitability for *P. chartarum* sporulation will increase with time in some South Island regions, but whether this will correlate with increasing facial eczema risk will depend on the prevalence of sporidesmin-producing isolates of *P. chartarum* in South Island pastures (Collin et al. 1998). A comprehensive package of multidisciplinary research that includes the ecology and population dynamics of the fungus, its interactions with biotic and abiotic variables, and spatially and temporally precise measurements of spore counts and facial eczema outbreaks is needed to enable truly robust predictions of how climate change will influence facial eczema severity in New Zealand.

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1 As we were completing this study, Anexa Veterinary Services provided us weekly spore counts from a range of Waikato farms that were geocoded by road name and locality, and these should prove useful for testing this and other models in the future.

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