

The possibility of establishment of dwarf bunt in New Zealand

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1. Executive Summary

The possibility of establishment of dwarf bunt in New Zealand.

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- The objective of this study was to assess the potential for dwarf bunt, a fungal disease of winter wheat caused by *Tilletia controversa* Kühn, to establish in New Zealand.
- Spore germination of *Tilletia controversa* depends on cool temperature conditions and exposure to a low level of ultraviolet (UV) radiation. A snow cover can modify microclimate conditions near the soil surface, allowing the spores to germinate at maximum rate.
- Because of mild winter temperatures and the predominant absence of snow cover in New Zealand, climatic conditions for dwarf bunt establishment are probably unsuitable in New Zealand wheat-growing areas, including Canterbury, Otago, Southland, Manawatu and Wairarapa. However, the degree of climate suitability was high in some localized mountain areas near Lake Wanaka and Lake Tekapo in the South Island.
- Grass hosts are available in areas with high climatic suitability for establishment of the dwarf bunt. However, it is unlikely that these grass hosts would contribute to the establishment of the disease under natural conditions without the introduction of large quantities of spores. Therefore, the risk of establishment for the disease in New Zealand would be low unless large numbers of spores were available in those areas.

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2. Abstract

Dwarf bunt caused by *Tilletia controversa* Kühn is a serious fungal disease of winter wheat. To assess the risk of *T. controversa* successfully establishing in New Zealand, the climate suitability for dwarf bunt in New Zealand was determined using a geographic information system (GIS) approach combined with a climate index for the establishment of dwarf bunt. The climate index was defined to incorporate current knowledge on climate conditions conducive to dwarf bunt development, namely cool temperatures and persistent snow cover or cloudy weather conditions. The climate index was determined for areas where dwarf bunt is known to occur using temperature, snow cover, and cloud cover data. Our results indicated that areas with a high value of the climate index were matched with regions where dwarf bunt has occurred, including the USA, Canada, Germany, and Russia. The values of the climate index were small in most areas of China, where the climatic risk of dwarf bunt establishment is reported to be extremely low. Thus, the climate index gave a good match with geographic distribution of dwarf bunt. Our results showed that the climate index values were small in New Zealand wheat-growing areas, e.g. Canterbury, Otago, Southland, Manawatu and Wairarapa. However, the values of the climate index were relatively high in mountain areas in the South Island. For example, there were two localized mountain areas near Lake Wanaka and Lake Tekapo where the climate index values were similar to that for Latvia, where dwarf bunt occurred in 2006. Nevertheless, it is unlikely that the disease would become established in the mountain areas without the introduction of large quantities of spores. New Zealand has mild winter temperatures and the ground surface is covered by snow for, at most, a short period of time during winter in wheat-growing areas. Therefore, New Zealand's climate is unsuitable for establishment of dwarf bunt in those areas. The chance of dwarf bunt establishment is also remote in mountain areas, where grasses are the most likely host plants, because dwarf bunt disease rarely occurs in grasses under natural conditions.

Key words: GIS, dwarf bunt, satellite, climate matching

3. Introduction

Tilletia controversa Kühn (common name: dwarf bunt) is an important pathogen of winter wheat in areas with extended snow cover (Trione & Hall 1986). Connors (1954) suggested that *T. controversa* may have been originally a parasite of native grasses in Europe and later became pathogenic on wheat. Dwarf bunt gets its name because infected plants have stunted growth compared with uninfected plants. The kernels of diseased plants are replaced by “bunt balls”, which contain masses of black spores with a foul odour. The bunt balls rupture at harvest, contaminating the grain, and the presence of disease also results in decreased yield. Dwarf bunt can cause market access restrictions (Mathre 1996).

T. controversa has been recorded on many grasses and cereals (Table 1). The current host list of *T. controversa* includes 24 genera and 65 species (Hardison et al. 1959; Schuhmann 1961; Purdy et al. 1963; Hoffmann & Waldher 1964; EPPO 2007): 4 species of *Aegilops*, 5 of *Agropyron*, 1 of *Agrostis*, 2 of *Alopecurus*, 1 of *Amblyopyrum*, 1 of *Arrhenatherum*, 1 of *Beckmannia*, 6 of *Bromus*, 1 of *Dactylis*, 10 of *Elymus*, 2 of *Eremopyrum*, 5 species of *Festuca*, 1 of *Holcus*, 4 of *Hordeum*, 1 of *Koeleria*, 4 of *Lolium*, 3 of *Poa*, 2 of *Pseudoroegneria*, 1 of *Secale*, 1 of *Taeniatherum*, 3 of *Thinopyrum*, 1 of *Trisetum*, and 2 of *Triticum*.

T. controversa can cause serious problems for grasses and wheat under favourable conditions. Dwarf bunt has caused significant loss of wheat crops in the USA (Goates & Peterson 1999). Hardison & Corden (1952) reported a serious outbreak in cultivated grasses in the Pacific Northwest region. Once the disease is established, it can affect future crops, because the spores of *T. controversa* can survive over a long period, e.g. 10 years, in the soil (Tyler & Jensen 1958).

However, it is rarely observed that the disease occurs in grasses under natural conditions (Hardison et al. 1959). For example, no dwarf bunt disease was observed in grass hosts in Canada (Baylis 1958). The occurrence of dwarf bunt in grasses was erratic even when artificial inoculation was used (Hardison et al. 1959). Goates & Peterson (1999) and Johnsson (1992) suggested that sufficient inoculum is needed to cause considerable problems, in conjunction with favourable weather conditions. In addition, Schuhmann (1961) doubted that grass hosts play an important role in perpetuating and spreading dwarf bunt in wheat.

3.1. CLIMATE CONDITIONS FOR SPORE GERMINATION

The life cycle of *T. controversa* is initiated by teliospore germination. The germination process can take one to three months. Temperature and light are major factors that influence spore germination process of the pathogen.

Lowther (1948) showed that spores of *T. controversa* require cool temperatures, e.g. 5°C, for germination. In his experiment, spores began to germinate in Petri dishes at the end of five weeks at 5°C and up to 50 per cent germination occurred after 49 days of incubation and increased to 75 per cent after 70 days. No spore germination was obtained at 10°C, whereas high percentages of germination were observed at 0°C after 104 days. Gassner & Niemann (1954) found that exposure of spores to preconditioning temperatures above (20°C) or below (-5°C) optimum caused a delay in germination if the spores were subsequently germinated at 3°C. Baylis (1958) also found that spore germination was delayed when the spores were placed at 5°C after they were exposed to a freezing temperature during the early part of incubation. In his work, it was shown that pre-incubation at 15°C or -5°C had no effect on the

rate of germination when the spores were exposed to 5°C after 4 weeks. Cardinal temperatures for dwarf bunt spore germination are: minimum -2°C, optimum 3 to 8°C, and maximum < 15°C (Hoffman 1982).

Gassner-Hoechst (1953) found that germination of dwarf bunt spores was dependent on light. No germination occurred unless the spores were exposed to light. Exposure to natural or artificial light resulted in good germination of spores. Gassner & Niemann (1954) reported that the greatest effect on germination was obtained by exposing the spores to light during the fifth or sixth week of incubation. However, stimulation occurred only when the spores were placed at a favourable temperature. Increasing duration of exposure to light and light intensity resulted in an increased stimulation. Baylis (1958) found that spores germinated in darkness after exposure to light for one week during the initial stages of incubation. However, a continuous exposure to light caused the spores to germinate at the maximum rate with minimum incubation.

Schauz (1977) found that the stimulating effect of light on germination depended on the quality of light. His work showed that spores germinated at maximum rate under short day conditions when the daily light period was varied. In continuous irradiation, spores began to germinate at 25 Lx and the best germination occurred at 2000 Lx. The germination rate was reduced when the spores were exposed to light at higher intensity. Additional work on light-induction of spore germination was conducted by Schauz & Rabie (1985). Their work indicated that spore germination in *T. controversa* was dependent on UV radiation (290-385 nm).

Wheat plants are mostly infected by *T. controversa* on or near the soil surface (Hofmann 1982). A snow cover changes microclimate near the soil surface. For example, snow cover deters occurrence of low ground surface temperatures. The effect of snow cover on the ground temperature is considerable during a cold season (Mann & Schmidt 2003). Fitton & Brooks (1931) observed that a persistent snow cover maintains the soil temperature at about 0°C on average even when the monthly air temperature is lower than freezing point. The difference between ground temperature and air temperature can range from about 10°C to 20°C during the cold season. For example, Gold (1967) observed that the monthly average temperature of a ground surface was up to 10°C warmer than the average air temperature when the surface was covered by snow. In addition, the full stimulating effects on spore germination can be obtained under snow cover because snow transmits little light. Therefore, snow cover could create favourable conditions for spore germination.

3.2. GEOGRAPHIC DISTRIBUTION

The acreage affected by dwarf bunt has been relatively small compared with the total worldwide wheat production areas, because a persistent snow cover occurs in only a small number of areas (Mathre 1996). However, dwarf bunt has been reported in many countries including the USA, Canada, Germany, Switzerland, Italy, Russia, and Sweden (Duran & Fischer 1956; CPCI 2008; Figure 1). According to EPPO (2007), the disease is present in Australia, Algeria, Libya, and Tunisia even though it is difficult to determine whether or not these records represent permanent establishment of the disease. For example, there was no record of dwarf bunt occurrence in North Africa or the Near East regions, except in Turkey (Mamluk 1998). Cherif et al. (1994) reported that common bunt occurred in Tunisia. However, dwarf bunt did not appear in their work. In Australia, dwarf bunt was reported to occur on *Hordeum leporinum* (McAlpine 1910). However, the recent work suggested that the pathogen was in fact *T. trabutii* (<http://www.padil.gov.au/pbt/>).

Dwarf bunt is not present in New Zealand. However, there could be potential for localized outbreaks in winter wheat areas when disease-conducive conditions occur in New Zealand. There are a number of grass species listed as hosts that are used for pasture production or that have been naturalized in New Zealand (Table 1). To define accurately the regional risk of *T. controversa* successfully establishing in New Zealand, we carried out analysis of climate conditions conducive to development of dwarf bunt.

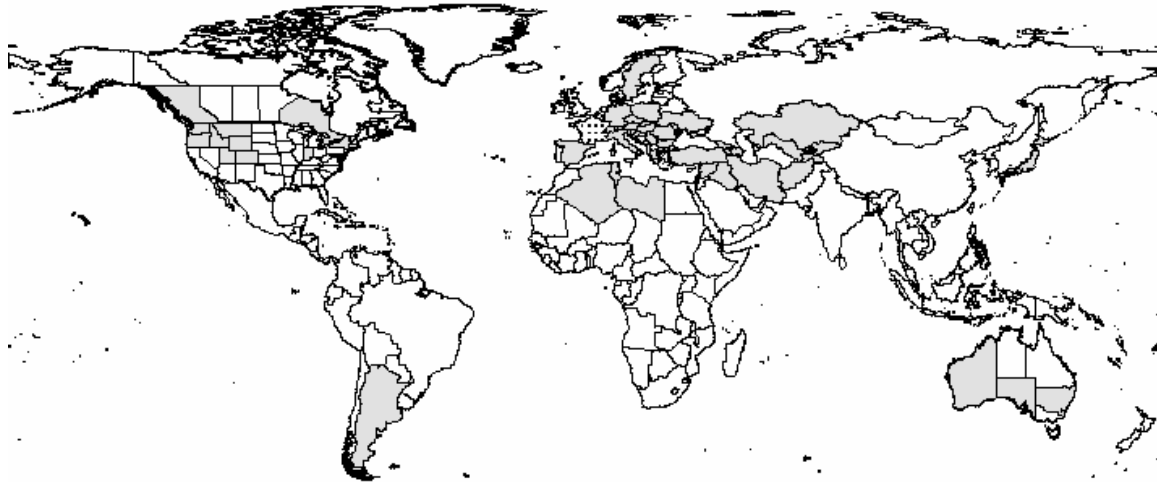


Figure 1. The known worldwide distribution of *Tilletia controversa* (CPCI 2008). Resolution of records for the USA and Australia are at the state level. Canadian records are at the provincial level of resolution. Shaded areas indicate administrative regions where *T. controversa* has been reported, and no more details are known. The disease is currently absent but was formerly recorded as present in France and Denmark. *T. controversa* is also present in Central and Southern Russia, and the Western Siberia region of the Russian Federation, which does not appear in the map.

Table 1: Host range^a of *Tilletia controversa*

Genera	Species	Availability ^b
<i>Aegilops</i>	<i>cylindrica</i> Host <i>triuncialis</i> L. <i>umbellulata</i> Zhuk. <i>ventricosa</i> Tausch	
<i>Agropyron</i>	<i>cristatum</i> (L.) Gaertn. <i>desertorum</i> (Fisch. ex Link) Schult. <i>diazii</i> Sennen <i>fragile</i> (Roth) P. Candargy <i>mongolicum</i> Keng	
<i>Agrostis</i>	<i>stolonifera</i> L.	+
<i>Alopecurus</i>	<i>arundinaceus</i> Poir. <i>mysuroides</i> Huds.	-
<i>Amblyopyrum</i>	<i>muticum</i> (Boiss.) Eig	
<i>Arrhenatherum</i>	<i>elatius</i> (L.) P. Beauv. ex J. Presl & C. Presl	+
<i>Beckmannia</i>	<i>syzigachne</i> (Steud.) Fernald	
<i>Bromus</i>	<i>carinatus</i> Hook. & Arn. <i>ciliatus</i> L. <i>erectus</i> Huds. <i>inermis</i> Leyss. <i>marginatus</i> Steud. <i>tomentellus</i> Boiss.	- +
<i>Dactylis</i>	<i>glomerata</i> L.	+
<i>Elymus</i> ^c	<i>arizonicus</i> (Scribn. & J. G. Sm.) Gould <i>canadensis</i> L. <i>caninus</i> (L.) L. <i>ciliaris</i> (Trin.) Tzvelev <i>epens</i> (L.) Gould <i>glaucus</i> Buckley <i>lanceolatus</i> (Scribn. & J. G. Sm.) Gould <i>repens</i> (L.) Gould <i>sibiricus</i> L. <i>trachycaulus</i> (Link) Gould ex Shinnars	
<i>Eremopyrum</i>	<i>orientale</i> (L.) Jaub. & Spach <i>triticeum</i> (Gaertn.) Nevski	
<i>Festuca</i>	<i>altissima</i> All. <i>arundinacea</i> Schreb. <i>idahoensis</i> Elmer <i>ovina</i> L. <i>rubra</i> L.	+ + +

Table 1: Host range^a of *Tilletia controversa* continued

Genera	Species	Availability
<i>Holcus</i>	<i>lanatus</i> L.	+
<i>Hordeum</i>	<i>brachyantherum</i> Nevski	
	<i>bulbosum</i> L.	
	<i>murinum</i> L.	-
	<i>vulgare</i> L.	+
<i>Koeleria</i> ^c	<i>cristata</i> (L.) Pers.	
<i>Leymus</i>	<i>multicaulis</i> (Kar. & Kir.) Tzvelev	
	<i>racemosus</i> (Lam.) Tzvelev	+
	<i>triticoides</i> (Buckley) Pilg.	
<i>Lolium</i>	<i>multiflorum</i> Lam.	+
	<i>perenne</i> L.	+
	<i>remotum</i> Schrank	-
	<i>temulentum</i> L.	-
<i>Poa</i>	<i>palustris</i> L.	-
	<i>pratensis</i> L.	+
	<i>trivialis</i> L.	+
<i>Pseudoroegneria</i>	<i>geniculata</i> (Trin.) Á. Löve	
	<i>spicata</i> (Pursh) Á. Löve	
<i>Secale</i>	<i>cereale</i> L.	+
<i>Taeniatherum</i>	<i>caput-medusae</i> (L.) Nevski	
<i>Thinopyrum</i>	<i>elongatum</i> (Host) D. R. Dewey	
	<i>intermedium</i> (Host) Barkworth & D. R. Dewey	-
	<i>pycnanthum</i> (Godr.) Barkworth	
<i>Trisetum</i> ^c	<i>cernuum</i> Trin.	
<i>Triticum</i>	<i>aestivum</i> L.	+
	<i>turgidum</i> L.	

a. This list of host ranges was obtained from Hardison et al. (1959); Schuhmann (1961); Purdy et al. (1963); Hoffmann & Waldher (1964); and EPPO (2007).

b. Availability of host plants in New Zealand was obtained from the New Zealand Plant database (<http://nzflora.landcareresearch.co.nz/>). + indicates that the geographic distribution of the given species is known, whereas – represents that the host plants have been recorded in New Zealand, but their geographic distribution is unknown.

c. In the given genera, the species identified as the host of dwarf bunt are not recorded in New Zealand. However, other species in the genera are recorded in New Zealand (Edgar & Connor 2000).

4. Materials and Methods

An index that represents climatic conditions for the establishment of dwarf bunt was defined in the present study. Sutherst & Maywald (1985) suggested the eco-climate index, which is derived from indices that represent degree of pathogen growth and stress. These indices are determined using temperature, moisture and day-length data. In contrast, temperature and snow cover are key variables for evaluating the likelihood of establishment of dwarf bunt, because the disease is likely to occur in areas that have persistent snow cover and cool winter temperatures (Trione 1982). Furthermore, a low amount of dwarf bunt can be induced under cool, cloudy and humid weather conditions (Zhang et al. 1995; Goates & Peterson 1999). Therefore, temperature, snow and cloud conditions were used to define the index to represent the possibility of the establishment of dwarf bunt.

4.1. CLIMATE DATA

Temperature data were obtained from the Climatic Research Unit, Norwich (New et al. 2002). The data have a spatial resolution of 10 arc min, which is about 18 km. This dataset contains 30-year averages for monthly mean temperature T_M and mean diurnal temperature range T_{DTR} . The climate data were derived from a set of station means for the period from 1961 to 1990 using spatial interpolation.

Snow cover data derived from satellite imagery were used in the present study. In 1997, the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information System (NOAA/NESDIS) developed the Interactive Multisensor Snow and Ice Mapping System (IMS) to produce daily snow and ice charts at approximately 24 km resolution (NOAA/NESDIS/OSDPD/SSD 2004). The IMS Daily Northern Hemisphere Snow and Ice Analysis data were used for a period from 1997 through 2007 in the present study.

The Environmental Data Record (EDR) was used to assess climatic conditions for dwarf bunt establishment in the southern hemisphere. The EDR is produced by the Fleet Numerical Meteorology and Oceanography Center (FNMOC) from the Defense Meteorological Satellite Program's (DMSP) Special Sensor Microwave/Imager (SSM/I) instrument aboard satellites (<http://www.class.ngdc.noaa.gov/>). Spatial resolution of the EDR product is about 50 km. Data obtained from DMSP-14 and DMSP-15 satellites were used in the present study. The EDR snow data were downloaded for a period from 2002 through 2008. Because the EDR are 6-hourly data, daily snow cover was calculated at each grid point.

The High Resolution Infrared Sounder (HIRS) data were used in our analysis (Wylie et al. 1994). The HIRS data are a part of the National Environmental Satellite Data and Information Service (NESDIS) operational sounding product. The HIRS data contain the average frequencies of clouds over 22 years at one-degree spatial resolution.

4.2. RULES FOR THE ESTABLISHMENT OF DWARF BUNT

A climate index for the establishment of dwarf bunt I was defined in the present study. Because dwarf bunt occurs over a long-term period, e.g. 6-12 weeks, climate conditions over several months were evaluated to determine the value of I . In the CLIMEX system suggested by Sutherst & Maywald (1985), the ecoclimatic index is used to compare climate conditions from regions where a pathogen was reported with those from other regions. The parameter for the ecoclimatic index is determined by the best-fit to the distribution of the pathogen, rather than by known climate conditions suitable for the pathogen. Therefore, the CLIMEX system leaves little room to incorporate rules on climate conditions favourable for the pathogen. In

contrast, we attempted to formulate rules to incorporate knowledge on climate conditions conducive to dwarf bunt development.

Johnsson (1992) reported that both low temperature during autumn and persistent snow cover during winter were associated with high incidence of dwarf bunt. In his work, temperature during winter was not important for the level of dwarf bunt attack, which is probably because snow cover can change ground surface temperatures. In the present study, a series of conditions conducive to development of dwarf bunt were stated in natural language applicable to both northern and southern hemispheres as follows:

- TMA = temperature is cool in mid autumn
- TLA = temperature is cool in late autumn
- CMA = cloud cover is dense in the month following mid autumn
- CLA = cloud cover is dense in the month following late autumn
- SMA = snow cover is persistent in the two months following mid autumn
- SLA = snow cover is persistent in the two months following late autumn.

where *MA* and *LA* indicate a month of mid autumn and late autumn, respectively. In the southern hemisphere, *MA* and *LA* are April and May, respectively. Those statements were combined into two rule statements to determine the risk of dwarf bunt outbreak as follows:

Rule 1. $(T_{MA} \text{ AND } C_{MA}) \text{ OR } (T_{MA} \text{ AND } S_{MA}) = T_{MA} \text{ AND } (C_{MA} \text{ OR } S_{MA})$ and

Rule 2. $(T_{LA} \text{ AND } C_{LA}) \text{ OR } (T_{LA} \text{ AND } S_{LA}) = T_{LA} \text{ AND } (C_{LA} \text{ OR } S_{LA})$.

4.3. INDICES FOR TEMPERATURE, SNOW COVER AND CLOUD

The temperature index *TI* was defined by Sutherst & Maywald (1985) as the product of two components, the effect of temperature on development rates I_Q and the reduced survival rates at high temperature I_H . To determine I_Q and I_H , four parameters, $DV0$, $DV1$, $DV2$, $DV3$, were used. In the present study, the cardinal temperatures for germination of the pathogen were used to determine the parameters for *TI*. Hoffmann (1992) redefined the cardinal temperatures for teliospore germination as: minimum -2°C , optimum $3-8^\circ\text{C}$ and maximum 15°C . Thus, the parameters for *TI* were defined as follows: $DV0 = -2$, $DV1 = 3$, $DV2 = 8$ and $DV3 = 15$.

The value of *TI* was calculated for mid autumn to early winter, e.g. April though June in the southern hemisphere. The *TI* values were obtained as Sutherst & Maywald (1985) had suggested. Monthly maximum T_X and minimum T_N temperatures were used as inputs to determine *TI* values. The values of T_X and T_N were obtained as follows:

$$T_X = T_M + 0.5 \cdot T_{DTR}, \text{ Eq. (1)}$$

And

$$T_N = T_M - 0.5 \cdot T_{DTR}. \text{ Eq. (2)}$$

Development of dwarf bunt can be deterred under very cold temperature conditions in mid autumn to early winter (Goates & Peterson 1999). High temperature during the period would also delay development of dwarf bunt (Baylis 1958). Thus, cold stress index *CSI* and heat stress index *HSI* were defined to take into account those as follows:

$$CSI = \{1 + \exp[-0.5 \cdot (WT_N + 10)]\}^{-1} \text{ Eq. (3)}$$

and

$$HSI = 1 - \{1 + \exp[-0.5 \cdot (WT_X - 10)]\}^{-1}, \text{ Eq. (4)}$$

where WT_N and WT_X represent minimum and maximum temperatures from mid autumn to early winter, respectively.

The frequency of days N_S during which snow cover existed in a month was calculated using snow data. The value of $N_S \in [0, 1]$ was determined from late autumn through winter, e.g. from May to August in the southern hemisphere, for each year. Then the N_S values were averaged over years during which snow data were available. The snow cover index SI was defined as follows:

$$SI = \{1 + \exp[-10 \cdot (N_s - 0.5)]\}^{-1}. \text{ Eq. (5)}$$

The cloud cover index CI was defined to take into account the influence of cloud cover on dwarf bunt outbreaks as follows:

$$CI = N_C \cdot f, \text{ Eq. (6)}$$

where $N_C \in [0, 1]$ represents monthly frequency of the dense clouds and f a correction factor. The dense cloud was defined as cloud with visible optical depths > 6 . The value of f was needed because cloud cover would be less effective than snow cover in development of dwarf bunt. Hoffmann (1982) reported that dwarf bunt occurred in about 60 percent of susceptible cultivars when weather conditions were favourable to disease development, e.g. a long persistent snow cover with cool temperature. In contrast, Zhang et al. (1995) reported that about 5 percent of wheat was infected in China under cloud cover conditions. In the present study, the value of f was assumed to be 0.08 at first. Later, the f value was heuristically adjusted to 0.8.

4.4. THE CLIMATE INDEX FOR THE ESTABLISHMENT OF DWARF BUNT

The temperature index TI , snow cover index SI , and cloud cover index CI were used to represent the statements for conditions conducive to dwarf bunt occurrence as follows:

- TMA = TIMA
- TLA = TILA
- CMA = CILA
- CLA = CIEW
- SMA = SILA \times SIEW
- SLA = SIEW \times SIMW

where EW and MW indicate early and mid winter, respectively. In the southern hemisphere, EW and MW are June and July, respectively. To evaluate the Rule 1 and Rule 2 statements, AND and OR operators were defined as follows:

$$C_x \text{ AND } C_y = C_x \cdot C_y \text{ and Eq. (7)}$$

$$C_x \text{ OR } C_y = C_x + C_y - C_x \cdot C_y, \text{ Eq. (8)}$$

where $C \in [0, 1]$. Using Eq. (7) and (8), those rule statements were rewritten to determine the value of R_1 and $R_2 \in [0, 1]$ as follows:

$$R_1 = TI_{MA} \cdot (CI_{LA} + SI_{LA} \cdot SI_{EW} - CI_{LA} \cdot SI_{LA} \cdot SI_{EW}) \text{ and Eq. (9)}$$

$$R_2 = TI_{LA} \cdot (CI_{EW} + SI_{EW} \cdot SI_{MW} - CI_{EW} \cdot SI_{EW} \cdot SI_{MW}) \text{ Eq. (10)}$$

The index I that represents the degree of suitability in climate conditions for the establishment of dwarf bunt in a given area was determined as follows:

$$I = \max(R_1, R_2) \cdot HSI \cdot CSI, \text{ Eq. (11)}$$

where HSI and CSI indicates the heat stress index and cold stress index.

The I values were determined at each grid of 10-minute resolution. The current distribution of dwarf bunt was used to derive threshold values of I that represent the likelihood of establishment of the disease. The threshold value was used to determine the possibility of establishment of dwarf bunt in New Zealand.

The Geographic Resources Analysis Support System (GRASS) was used to compute the value of indices. The GRASS is a geographic information system (GIS) used for geospatial data management and analysis, maps production, spatial modelling, and visualization. The GRASS is official project of the Open Source Geospatial Foundation (<http://www.osgeo.org/>).

5. Results

The I value >0.15 seemed to explain occurrence of dwarf bunt in all known regions except seven countries: Denmark, Luxembourg, Australia, Syria, Algeria, Tunisia, and Libya. In Denmark and Luxembourg, the maximum I values were 0.13 and 0.08 in a localized area, respectively. The I value was < 0.05 in Algeria, Libya, Tunisia, and Syria, where the disease was rarely reported to the best of our knowledge.

The I values were > 0.15 on opposite sides of North America, as illustrated in Figure 2A. In the USA, the I values were > 0.15 in relatively large areas of Idaho, Utah, Washington, Oregon, and Montana. Areas in New York and Michigan states also had I values > 0.15 . The I values were > 0.15 in localized areas in Colorado and Wyoming. In Canada, the I values were > 0.15 in western British Columbia and south-western Ontario.

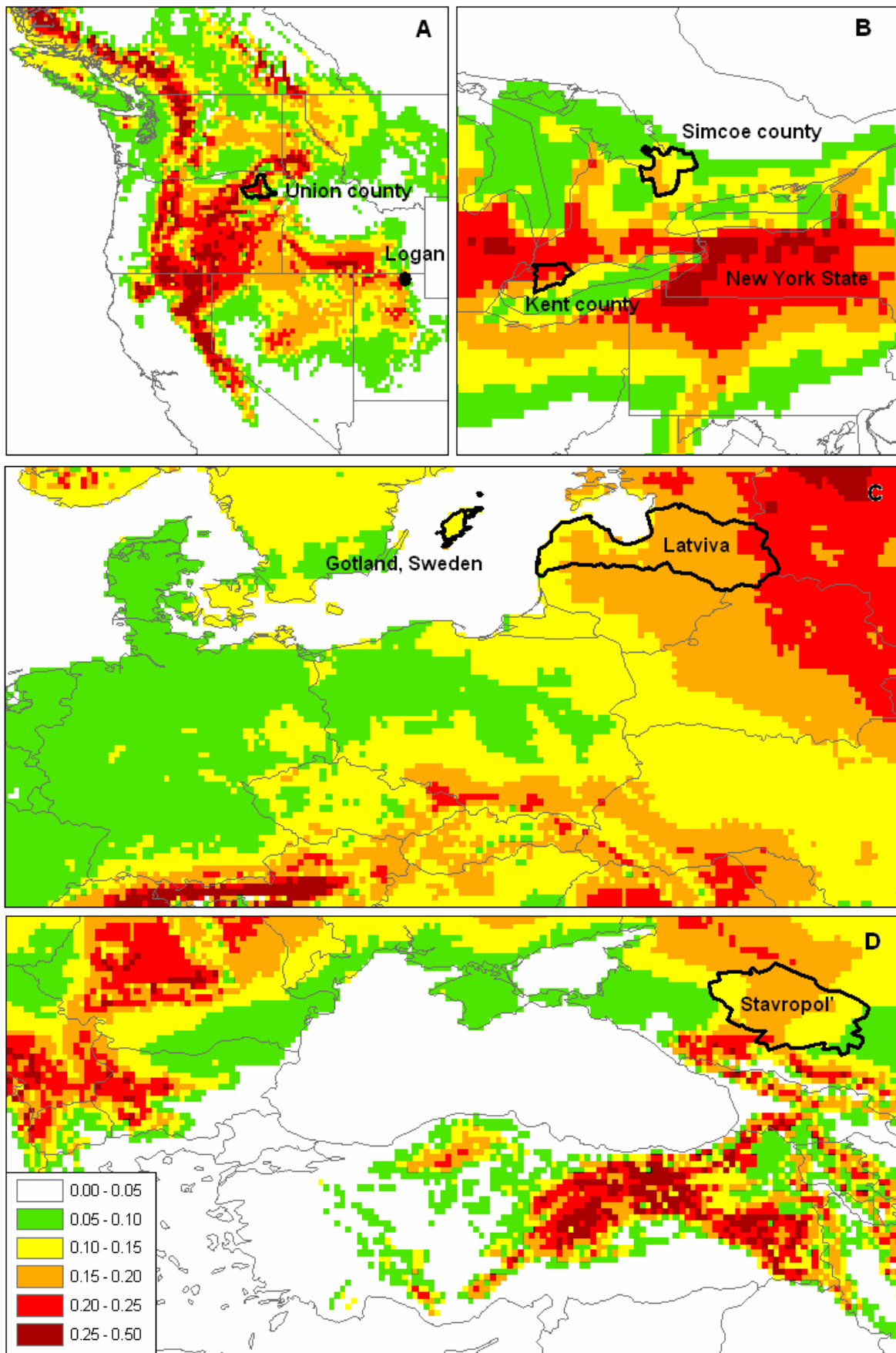


Figure 2. The risk index for establishment of dwarf bunt: A) the Pacific West region in the USA; B) the Ontario region in Canada; C) in Europe; C) in the eastern Balkans and southern Russia.

In Europe, the *I* values were relatively higher, e.g. > 0.25, in mountain areas including southern Germany, Switzerland and Austria (Figure 2C). The *I* value was > 0.15 in relatively small areas in south-eastern Sweden. However, there were large areas where the *I* value was between 0.1 and 0.15. South-western Russia, and the Balkans had areas with high *I* values, e.g. > 0.25 (Figure 2D).

In Central and West Asia, the *I* values were > 0.25 in many regions (Figure 2D and 3). For example, there was a large area where the *I* value was > 0.25 in Turkey and Kazakhstan. In contrast, the *I* values were considerably low in East Asia including China (Figure 3). Most areas in China had an *I* value < 0.05, while north-eastern regions had relatively high *I* values compared with other parts of the country.

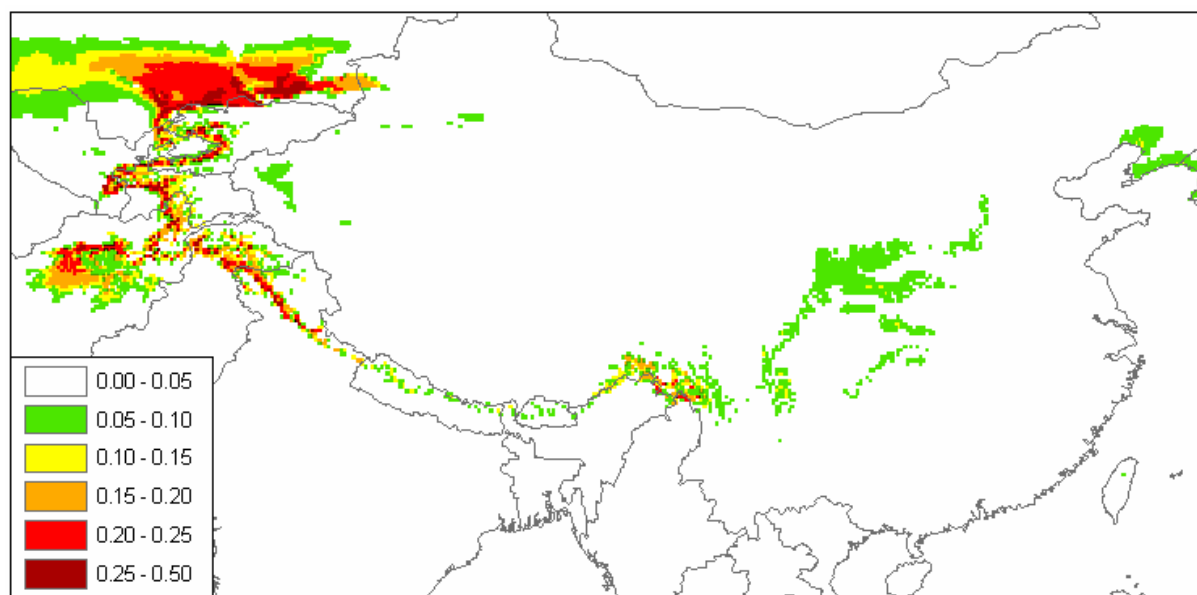


Figure 3. The risk index for establishment of dwarf bunt in the Western Asia and China.

In the southern hemisphere, the total areas with *I* values > 0.15 were smaller than in those in the northern hemisphere. However, mountain areas in Argentina had relatively high *I* values, e.g. > 0.25. The *I* values were relatively high, e.g. > 0.15, in the southern part of that country.

In New Zealand, the *I* value was greater in the South Island than the North Island (Figure 4). Overall, the *I* values were relatively high in the south-western part of the South Island including Westland, the Queenstown Lakes, Mackenzie Country, and the Milford and Fiordland areas in Southland. Furthermore, there were localized areas with *I* values > 0.15. In some other mountain areas, the *I* values were between 0.1 and 0.15, indicating a marginal risk of dwarf bunt establishment.

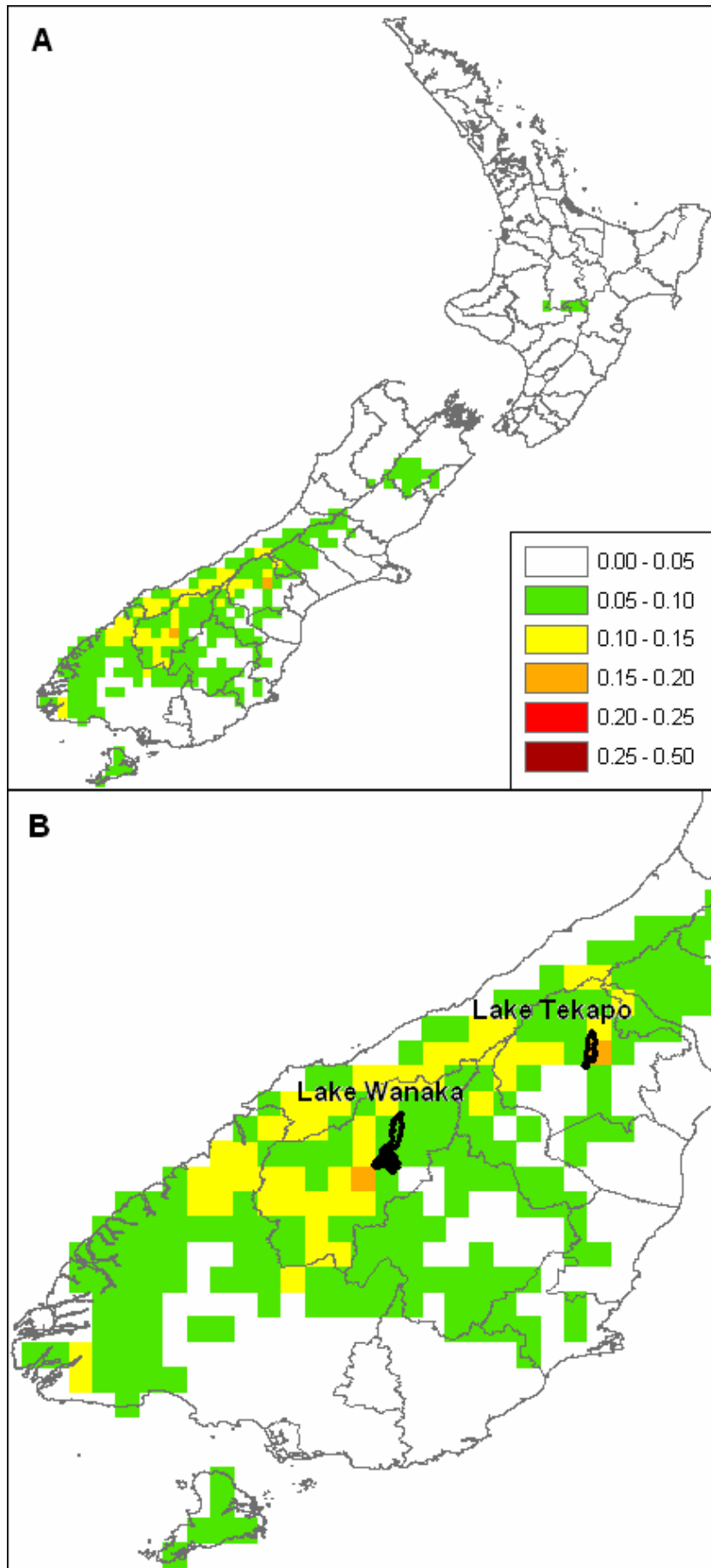


Figure 4. The risk index for establishment of dwarf bunt in New Zealand.

6. Discussion

This study has shown that New Zealand's climate is unsuitable for the establishment of dwarf bunt in wheat-growing areas (Figure 4A). The main winter wheat-growing areas are the south eastern part of the South Island, including the Canterbury region from Cheviot to Oamaru and the Southland region around Winton and Balfour. In the North Island, wheat is grown in the Manawatu and Wairarapa regions, as well as in southern Hawke's Bay. In our analysis, areas with the I values > 0.05 rarely corresponded with wheat production areas in those regions. This is because New Zealand has mild winter temperatures without persistent snow cover in most areas.

However, our results indicated that the climate conditions were relatively suitable for establishment of dwarf bunt in mountain areas of the South Island (Figure 4B). For example, the I values were > 0.15 in two areas near Lake Wanaka and Lake Tekapo (Figure 5). In these areas, alternative host species for dwarf bunt *Bromus inermis*, *Festuca rubra*, *Holcus lanatus*, and *Poa pratensis* have been recorded (Figures A1-A5). Nonetheless, the likelihood of dwarf bunt becoming established in these mountain areas is negligible without the introduction of large quantities of spores. Goates & Peterson (1999) showed that at least 2×10^6 spores/g of seed would be required to cause dwarf bunt by seed inoculation. Purdy et al. (1963) suggested that the dwarf bunt disease rarely occurs in grasses under natural conditions. Thus, the chance that dwarf bunt could become established in New Zealand would be remote unless a tremendous number of spores were imported and distributed.

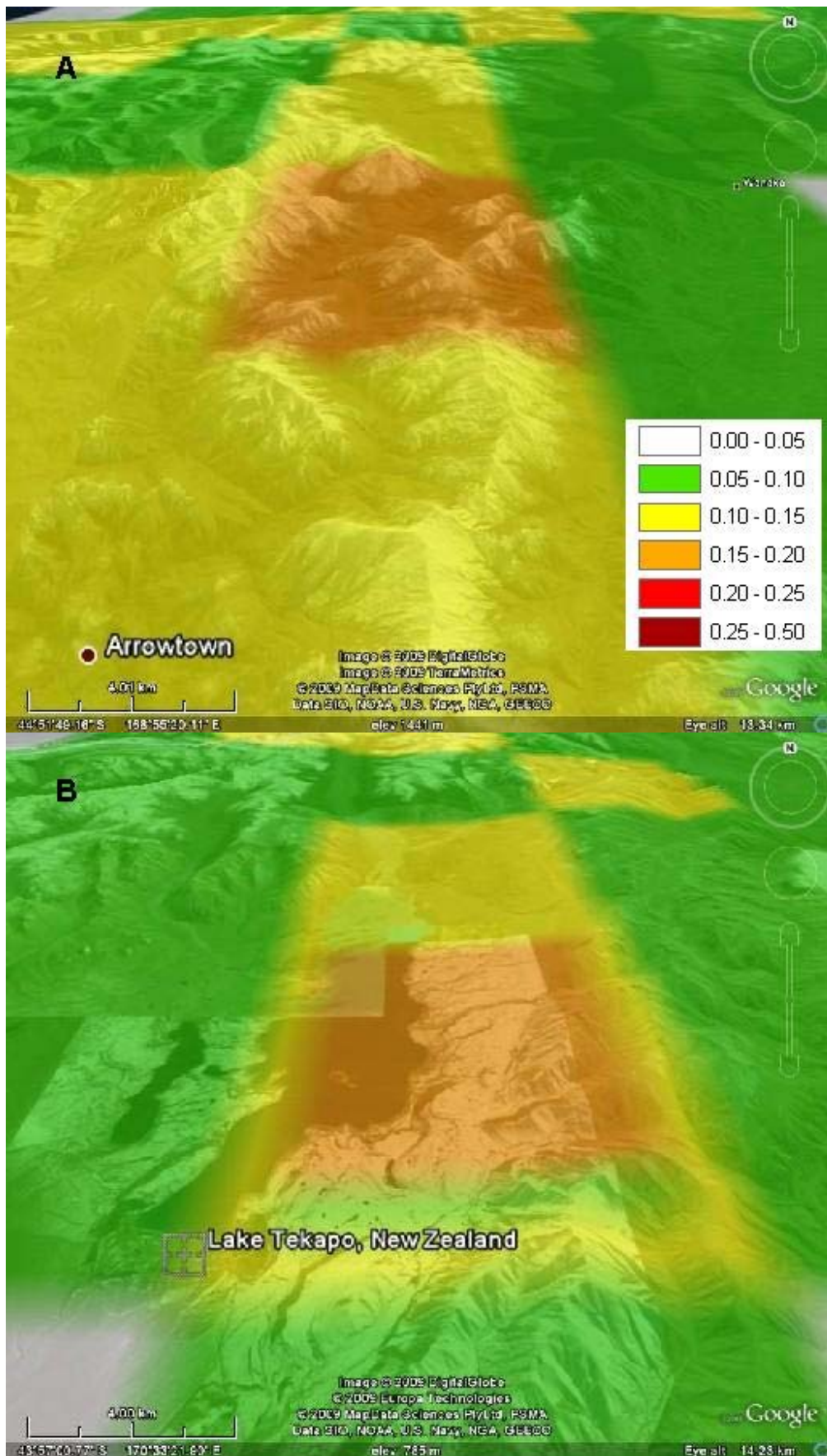


Figure 5. The risk index for establishment of dwarf bunt in areas: A) near Lake Wanaka; B) near Lake Tekapo

Our results showed that areas with high values of *I* were matched with regions where dwarf bunt caused problems in the USA and Canada (Figures 2A and 2B). According to Goates & Peterson (1999), weather conditions conducive to the disease commonly occur at Logan, Utah. Hardison & Corden (1952) reported that cultivated grasses were infected in Union County, Oregon. In these areas, the *I* values were > 0.2 in our study (Figure 2A). In New York State, the disease occurred in 10 counties adjacent to Lake Ontario (Baylis 1958, Tyler & Jensen 1958). Connors & Savile (1948) reported that the disease has been reported in Ontario, Canada. In these regions, the *I* values were > 0.15 (Figure 2B). For example, the *I* values were > 0.15 in large areas of Simcoe and Kent Counties, Ontario, where the disease was recorded (Baylis 1958).

In Europe, dwarf bunt has caused problems in the wheat-growing regions in Germany, Russia, and the Balkans (Schauz 1980). Our results indicated that the geographical distribution of high risk areas included those regions (Figures 2C and 2D). In 2006, dwarf bunt was observed on winter wheat in different geographical regions in Latvia for the first time (Priekule 2007). In Latvia, persistent snow cover occurs sporadically. However, our results indicated that the risk of dwarf bunt establishment was relatively high in most regions in Latvia. In Sweden, the disease has been reported in the island of Gotland (Johnsson 1992). According to Johnsson (1992), severe infection of dwarf bunt did not always occur in the area under favourable weather conditions. In our study, there was a large area with the *I* value between 0.1 and 0.15 on the island. Furthermore, the *I* value was > 0.15 in a localized area in the southern part of the island. In Russia, dwarf bunt caused 54 percent loss of wheat crop in the Stavropol' region in Russia in 1957 (Rusakov 1959). Our analysis showed that areas with the *I* value > 0.15 corresponded reasonably well with the region in Russia.

Trione & Hall (1986) suggested that the acreage of potential sites for dwarf bunt establishment was relatively small in the winter wheat-growing regions of China. Mathre (2000) reported that climate conditions for dwarf bunt establishment were unsuitable in China unless an excessive number of teliospores were introduced into the country. Our results agreed that the climatic risk of dwarf bunt establishment was extremely small in most areas of China (Figure 3). However, Zhang et al. (1995) reported that dwarf bunt occurred in north-eastern China after inoculation. Our results indicated that the risk in this region was greater than in other regions in China.

In summary, the risk of establishment for dwarf bunt in New Zealand would be low under natural conditions. Worldwide areas with a high value of the climate index were matched with regions where dwarf bunt has occurred. Our results indicated that climatic suitability for establishment of the dwarf bunt is low in most regions in New Zealand. The value of climate index is high in localized mountain areas where grass hosts are available in New Zealand. However, it is unlikely that those grass hosts would contribute to the establishment of the disease under natural conditions.

7. Acknowledgements

The IMS Daily Northern Hemisphere Snow and Ice Analysis data used in the present study were provided by the NSIDC, Boulder, Colorado, USA, from their website at <http://nsidc.org>.

We thank R. Hanson at Plant & Food Research for providing information on wheat-growing regions.

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9. Appendices

Appendix 1 – Availability of host plants

Availability of plant hosts in New Zealand for dwarf bunt, a fungal disease of winter wheat caused by *Tilletia controversa* Kühn, was determined using the New Zealand Plant database (<http://nzflora.landcareresearch.co.nz>). The geographic distributions of each host listed in Table 1 were combined to generate the risk map of dwarf bunt establishment (Figure A1). The geographic distributions of the host plants in New Zealand appear in Figures A2-A5.

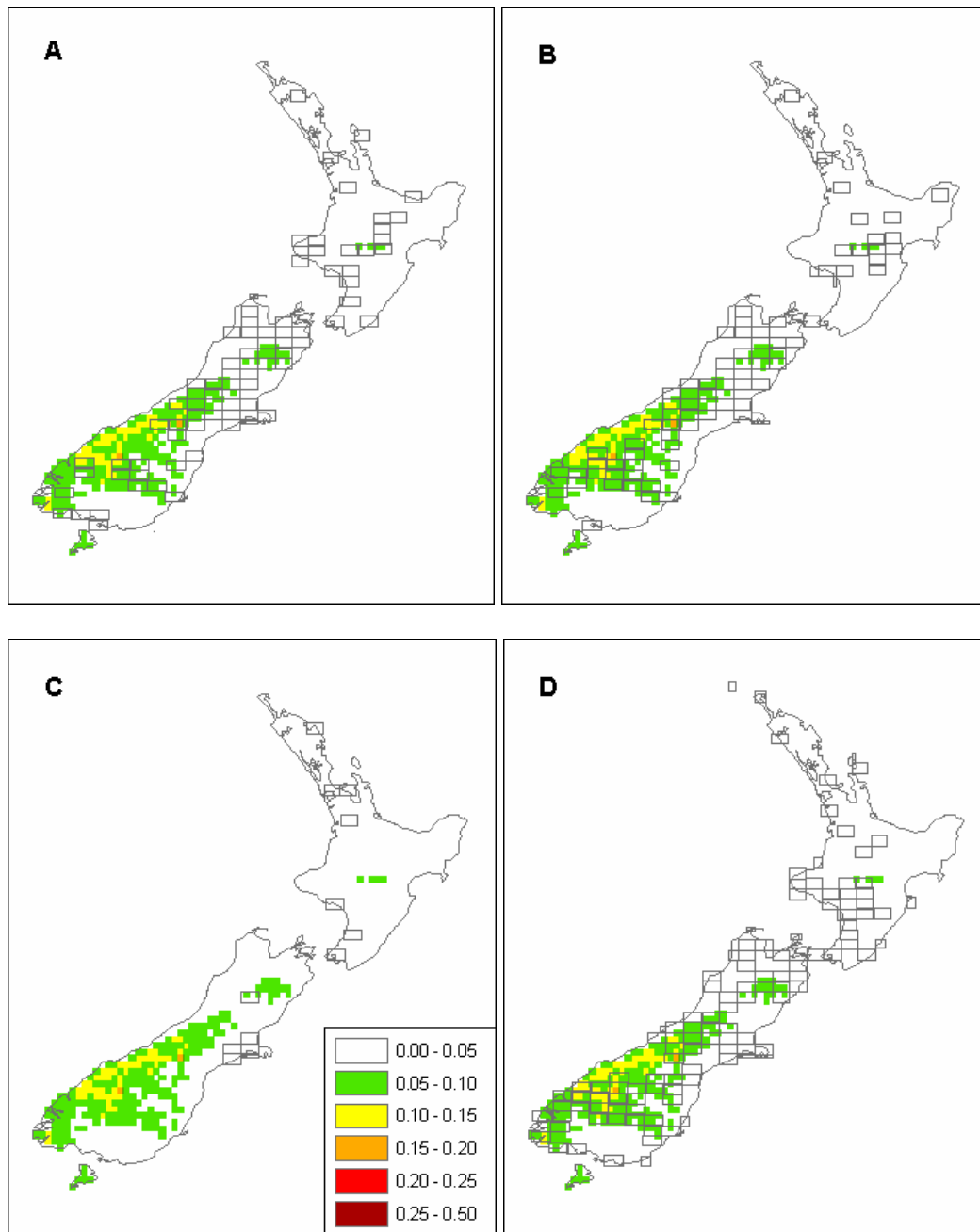


Figure A1. The risk index for establishment of dwarf bunt in areas where host plants are recorded in New Zealand: A) species identified as hosts of the disease; B) species in the genera *Festuca*; C) species in the genera *Lolium*; D) species in the genera *Poa*. Availability map of host plants in New Zealand was produced using records in the New Zealand Plant database (<http://nzflora.landcareresearch.co.nz/>). Each rectangle represents a New Zealand 260 Map Series (1:50,000) Map Sheet.

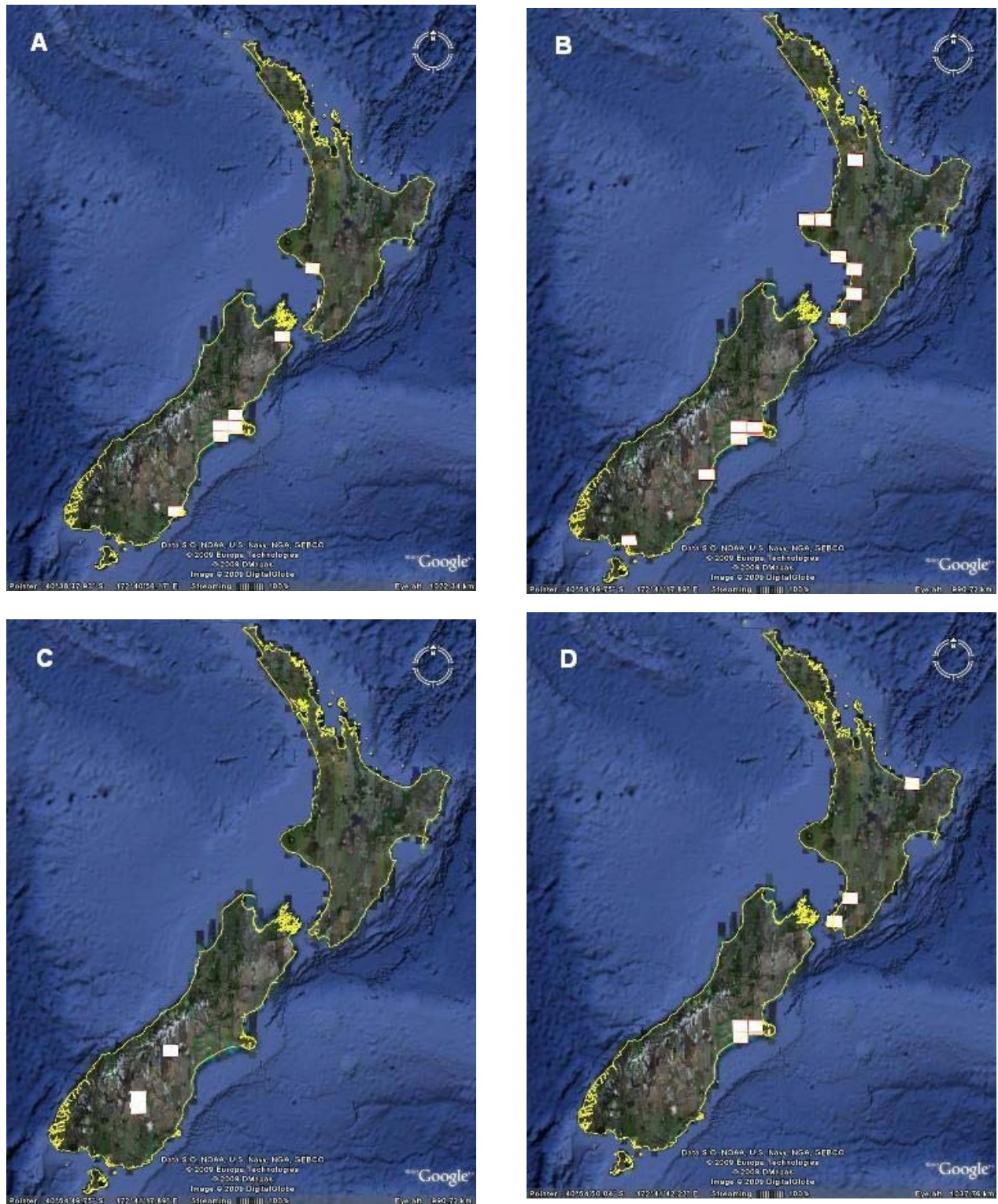


Figure A2. The geographic distribution of host plants of *Tilletia controversa* (casual agent of dwarf bunt disease) in the genera *Agrostis*, *Arrhenatherum*, *Bromus* and *Dactylis* in New Zealand (Edgar & Connor 2000): A) *Agrostis stolonifera*, which is distributed throughout the North and South Islands; B) *Arrhenatherum elatius*; C) *Bromus inermis*, which is located in South Auckland (Ruapuke) and Bay of Plenty (Whakatane) in the North Island, and Central Otago (near Luggate, near Alexandra) in the South Island; D) *Dactylis glomerata*, which is mostly distributed in the east from East Cape southwards in the North Island. It is also common in the east in the upper half of the South Island. Availability map of host plants in New Zealand was produced using records in the New Zealand Plant database (<http://nzflora.landcareresearch.co.nz/>).

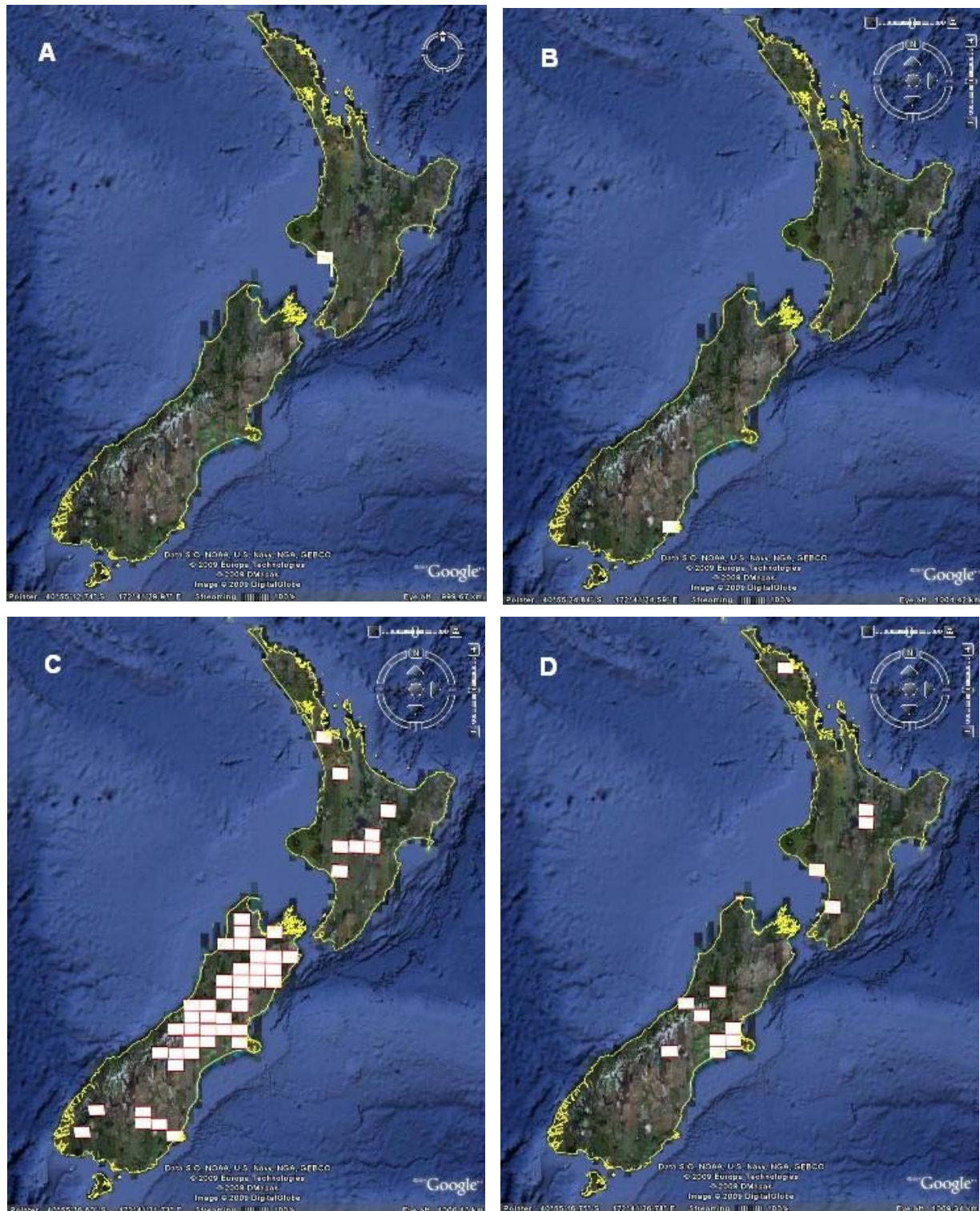


Figure A3. The geographic distribution of host plants of *Tilletia controversa* (casual agent of dwarf bunt disease) in the genera *Festuca* and *Holcus* in New Zealand (Edgar & Connor 2000): A) *Festuca arundinacea*; B) *Festuca ovina*; C) *Festuca rubra*; D) *Holcus lanatus* is distributed throughout the North and South Islands; The other species in the genera *Festuca* are distributed mostly in tussock grasslands. Availability map of host plants in New Zealand was produced using records in the New Zealand Plant database (<http://nzflora.landcareresearch.co.nz/>).

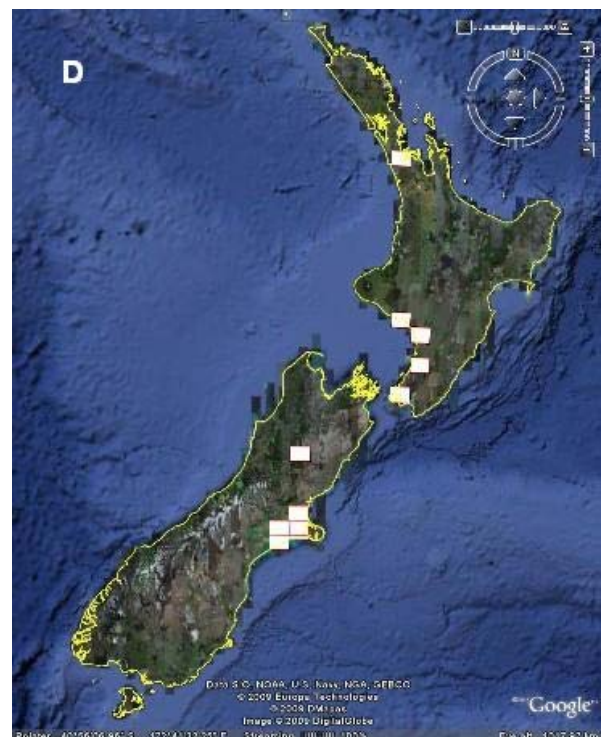
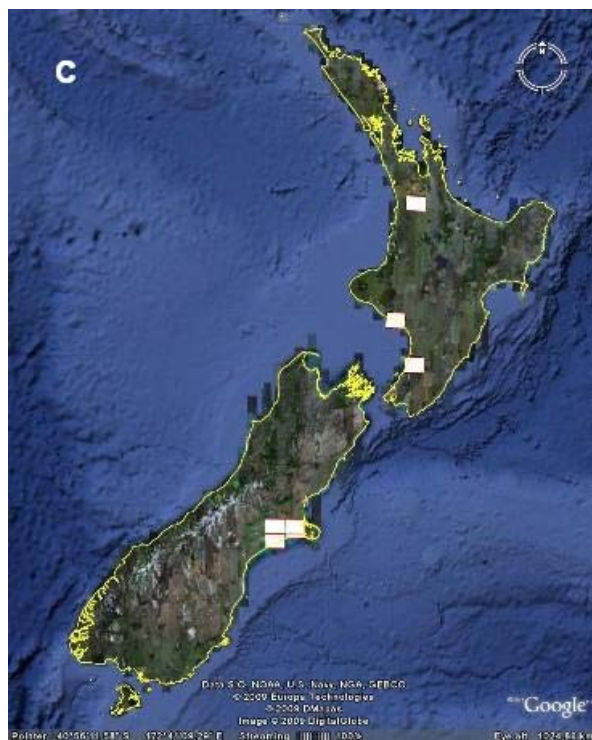
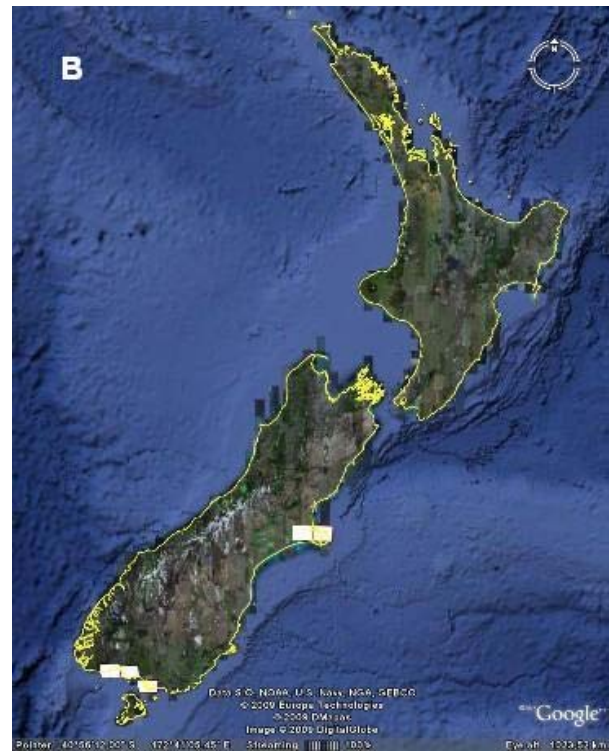


Figure A4. The geographic distribution of host plants of *Tilletia controversa* (casual agent of dwarf bunt disease) in the genera *Hordeum*, *Leymus*, and *Lolium* in New Zealand (Edgar & Connor 2000): A) *Hordeum vulgare* is occasionally found in an area as a result of an escape from cultivation; B) *Leymus racemosus* is in Canterbury (Gore Bay, Hawarden, near Christchurch, Banks Peninsula, north of Timaru), Central Otago (Cromwell), and Southland (Bluff) in the South Island; C) *Lolium multiflorum*; D) *Lolium perenne*. In New Zealand, the species in the genus *Lolium* are distributed throughout the North and South Islands. Availability map of host plants in New Zealand was produced using records in the New Zealand Plant database (<http://nzflora.landcareresearch.co.nz/>).

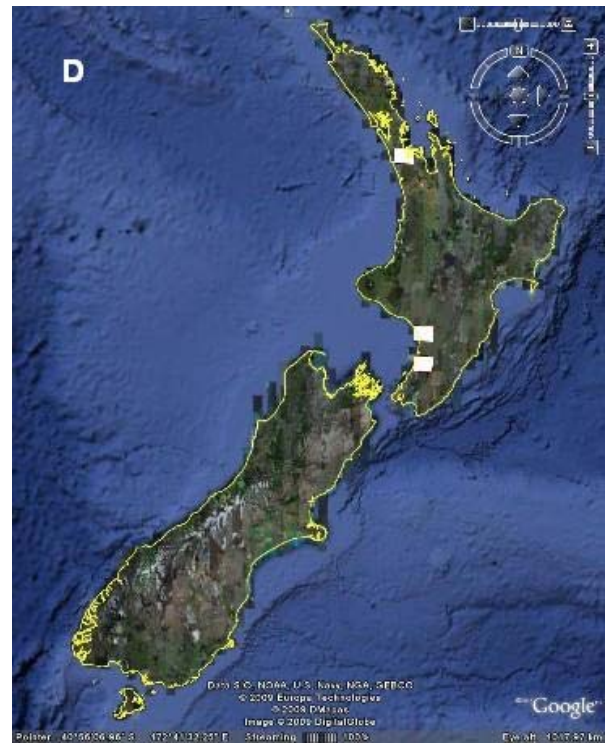
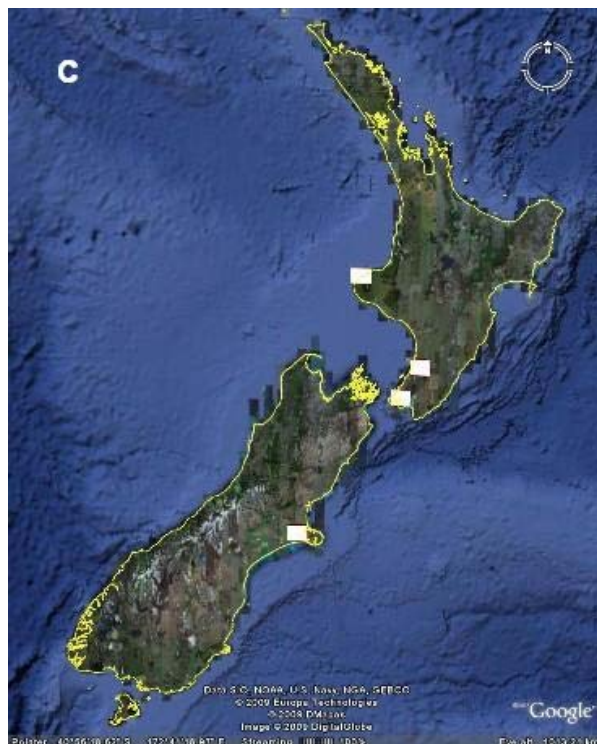
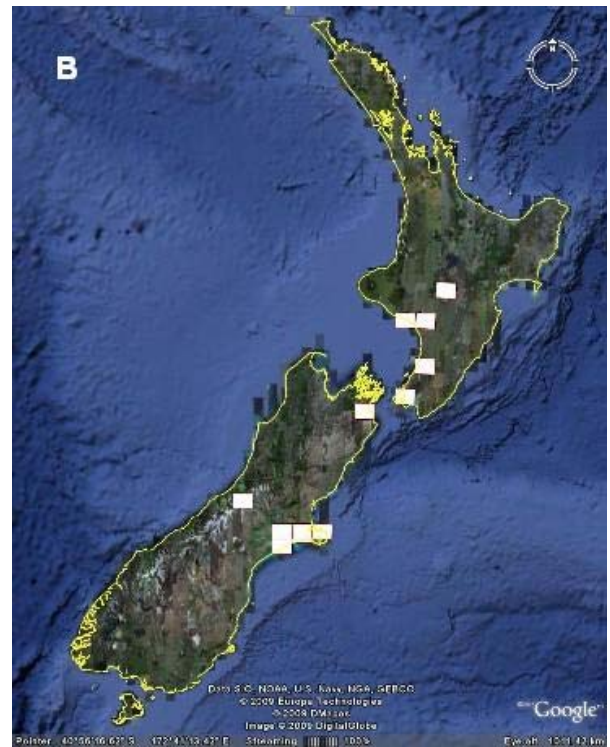


Figure A5. The geographic distribution of host plants of *Tilletia controversa* (casual agent of dwarf bunt disease) in the genera *Poa*, *Secale* and *Triticum* in New Zealand (Edgar & Connor 2000): A) *Poa pratensis*; B) *Poa trivialis*; C) *Secale cereale*; D) *Triticum aestivum*. The species in the genus *Poa* are distributed throughout New Zealand. Availability map of host plants in New Zealand was produced using records in the New Zealand Plant database (<http://nzflora.landcareresearch.co.nz/>).

Appendix 2 - Summary of climate data

In general, regions where the disease is known to occur match areas with a persistent snow cover over the winter in northern hemisphere (Figure A6). For these regions, the dense cloud cover, which has a visible optical depth > 6 , occurred relatively frequently (Figure A7). The average value of temperature index was relatively low in the known dwarf bunt regions because monthly minimum temperatures in these regions are considerably lower during winter (Figure A8). In New Zealand, there are small numbers of areas with a long persistent snow cover and dense cloud cover (Figure A9). The values of the temperature index were low in the northern part of the North Island because of warm temperatures. In the mountain areas in the South Island on the other hand, the temperature index values were low because of freezing temperatures during winter. However, the values of the temperature index were relatively high in most areas.

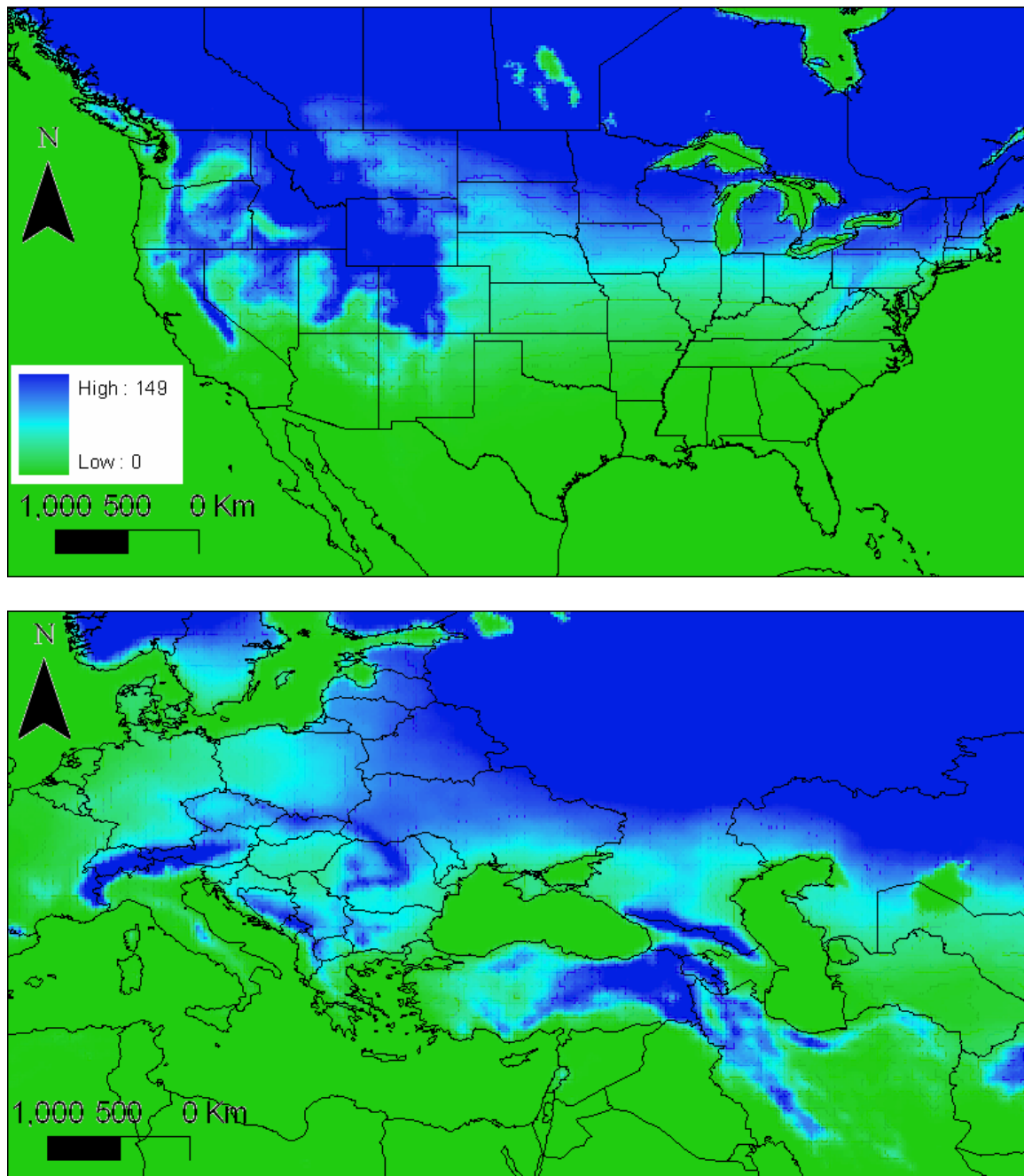


Figure A6. The average number of days during which snow was present from October to February in 1997-2007: A) in the USA; B) in Eurasia.

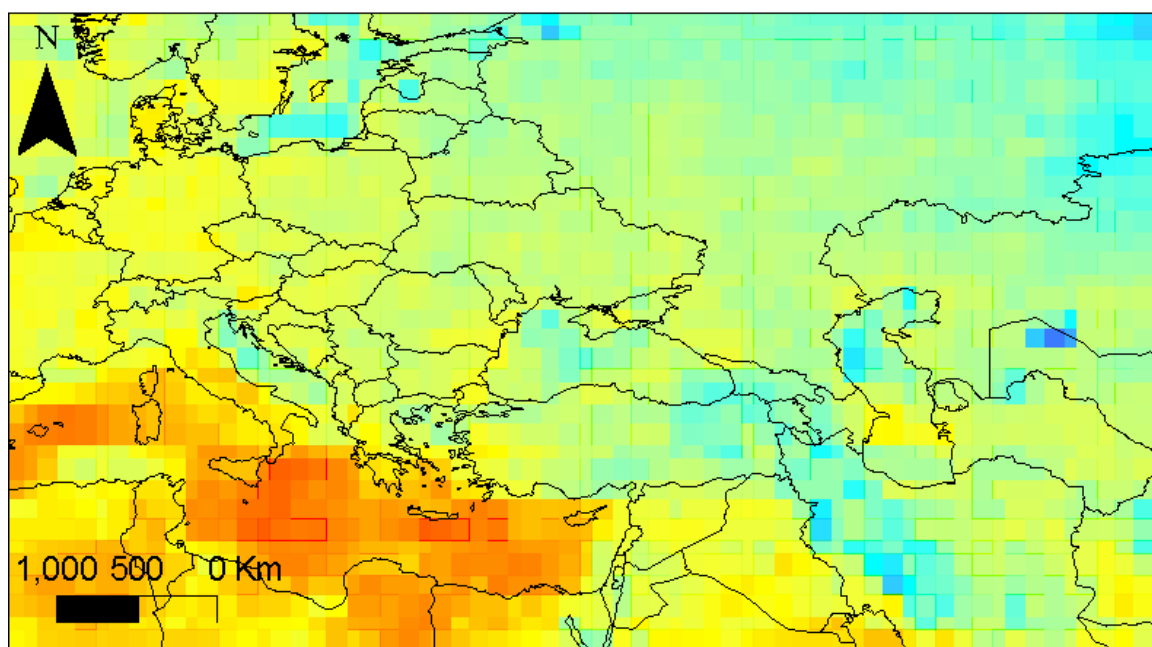
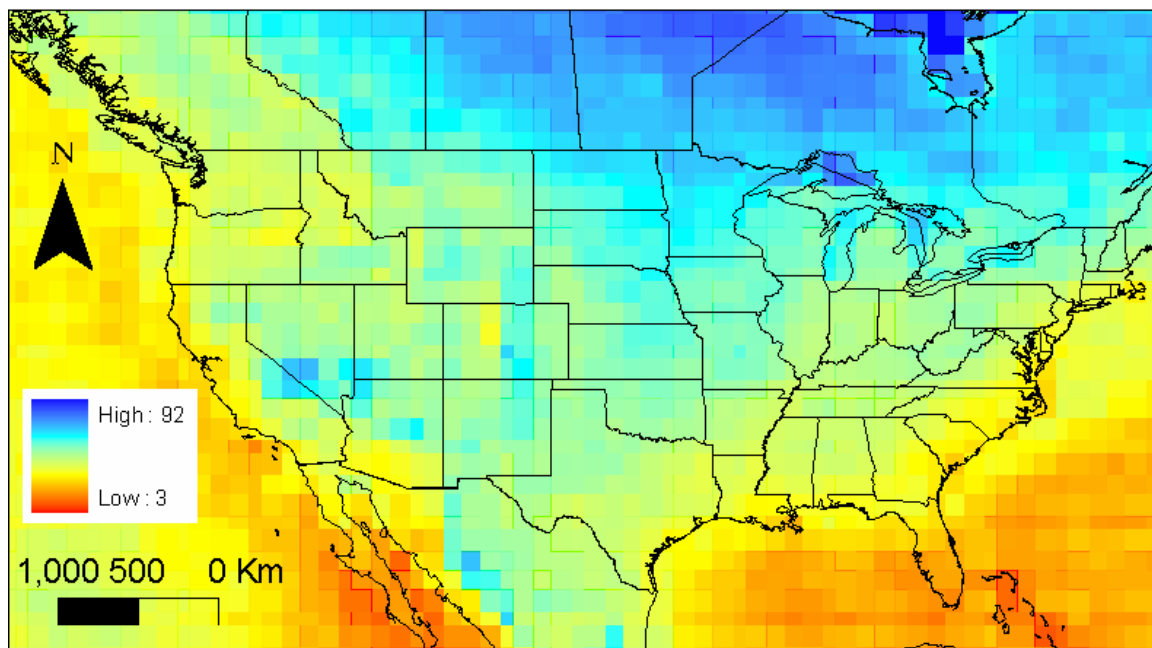


Figure A7. Average frequency of dense cloud cover that had optical depth > 6 from November to February: A) in the USA; B) in Eurasia.

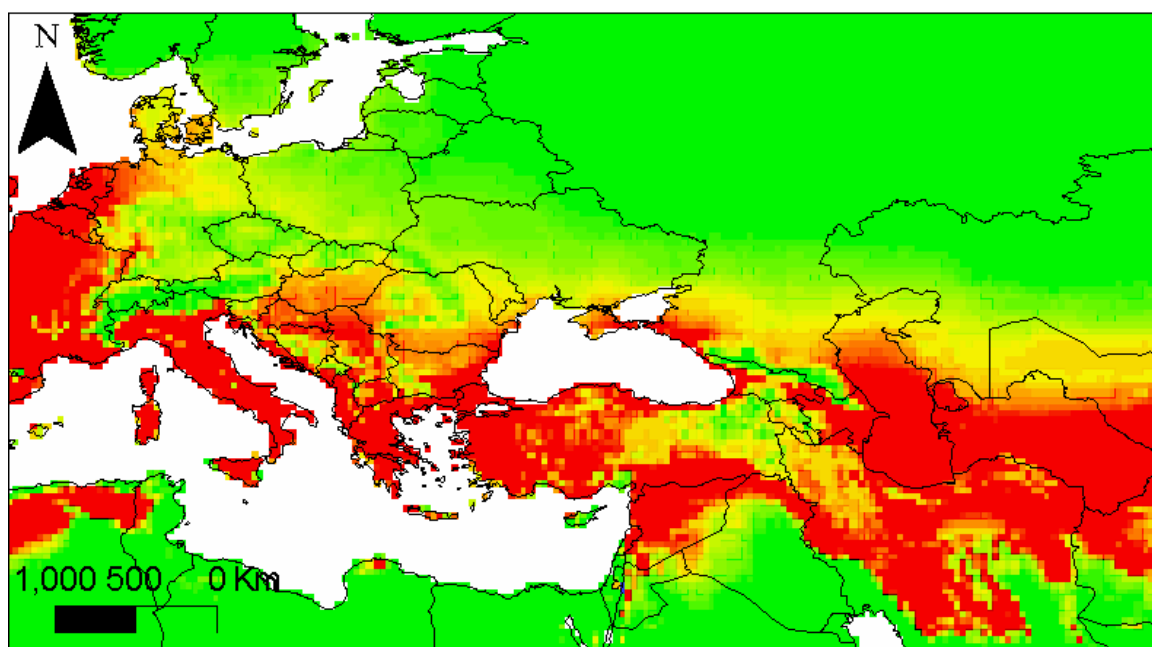
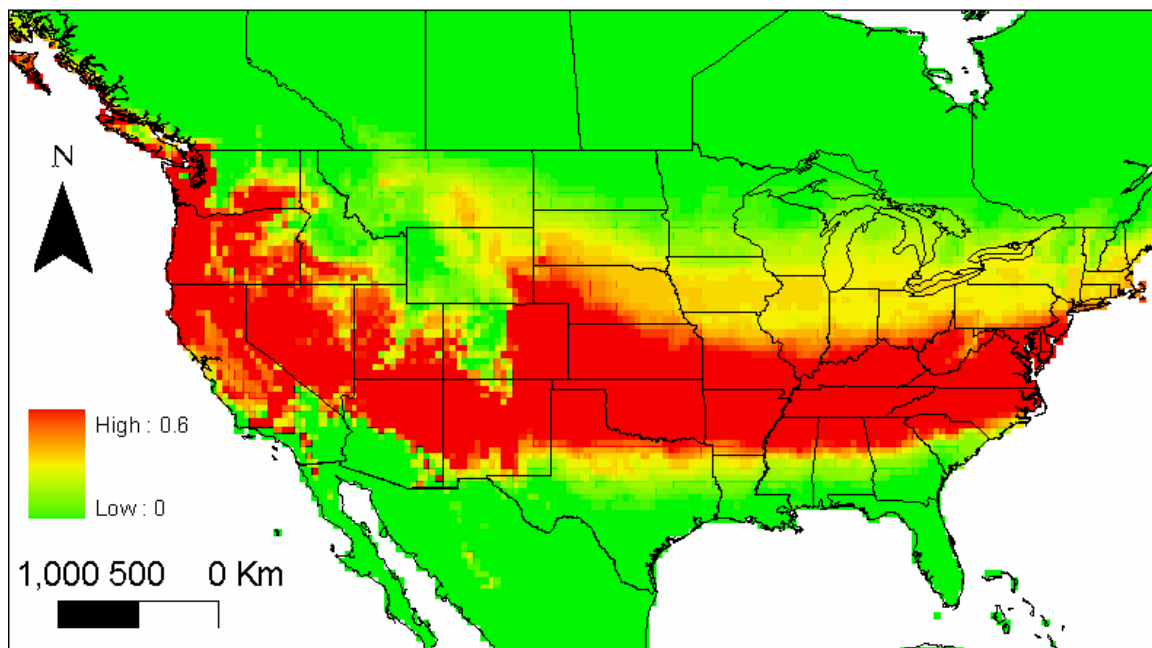


Figure A8. Average temperature index suggested by Sutherst & Maywald (1985) from November to February: A) in the USA; B) in Eurasia.

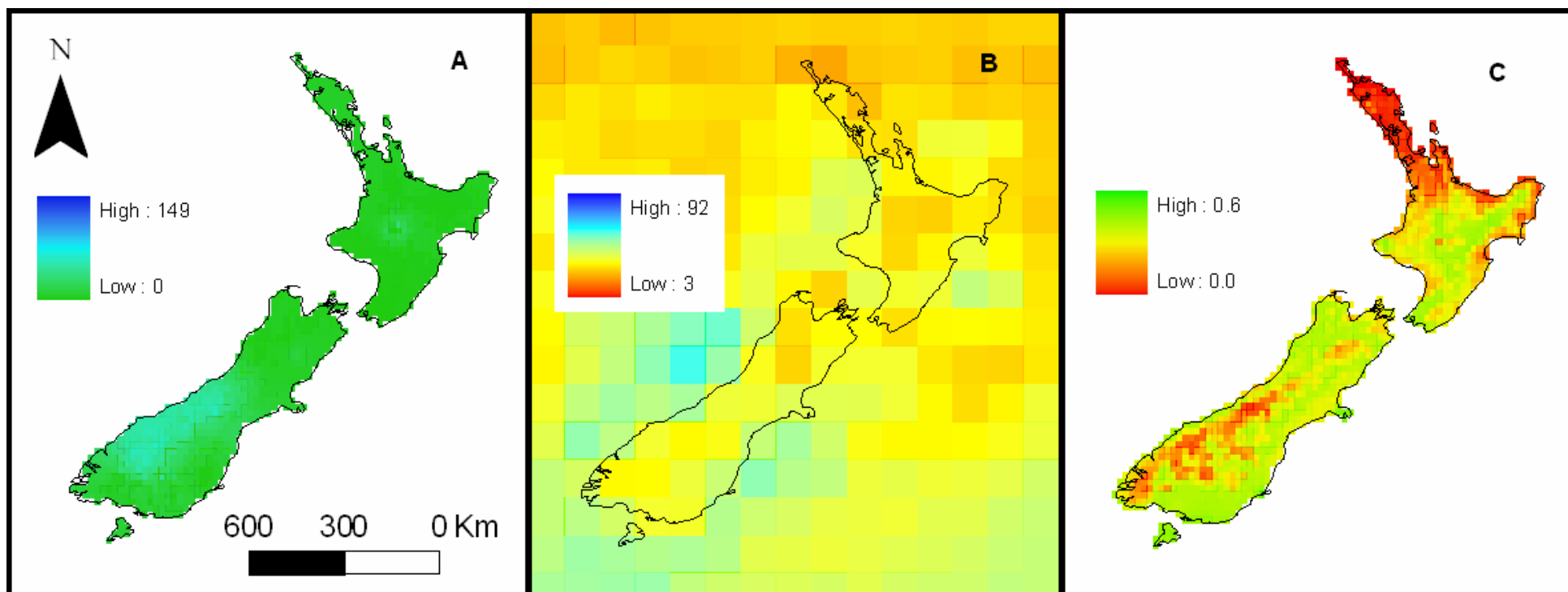


Figure A9. Summary of New Zealand climate data used in the present study: A) the average number of days during which snow was present from April to August in 2003-2008; B) average frequency of dense cloud cover that had optical depth > 6 from May to August, Eurasia; C) average temperature index suggested by Sutherst & Maywald (1985) from May to August.

Appendix 3 - A source code to determine the climate index

```
#!/bin/sh
# grass script to determine the climate index for the establishment of dwarf bunt
g.mapset -c DINDEX
g.region -p n=90 s=-90 w=-180 e=180 rows=1080 cols=2160

# file name
TARGET=DwarfIndex

# cloud correction factor
HFTR=0.8

# parameters for snow cover index
SPA=-10
SPB=0.4

# parameters for cold stress index
CPA=-0.5
CPB=10

# parameters for heat stress index
HPA=0.5
HPB=10

# hemisphere loop
HS=("NH" "SH")
for H in `seq 0 1`;
do

if [ $H -eq 0 ]; then

# NH
MO=("oct" "nov" "dec" "jan" "feb")

SNW0="1/(1+exp(${SPA}*(imsavg_${MO[0]}@IMSNH/31 - ${SPB})))"
SNW1="1/(1+exp(${SPA}*(imsavg_${MO[1]}@IMSNH/30 - ${SPB})))"
SNW2="1/(1+exp(${SPA}*(imsavg_${MO[2]}@IMSNH/31 - ${SPB})))"
SNW3="1/(1+exp(${SPA}*(imsavg_${MO[3]}@IMSNH/21 - ${SPB})))"

else

MO=("apr" "may" "jun" "jul" "aug")

SNW0="1/(1+exp(${SPA}*(edr${MO[0]}_idw@EDRSH/30 - ${SPB})))"
SNW1="1/(1+exp(${SPA}*(edr${MO[1]}_idw@EDRSH/31 - ${SPB})))"
SNW2="1/(1+exp(${SPA}*(edr${MO[2]}_idw@EDRSH/30 - ${SPB})))"
SNW3="1/(1+exp(${SPA}*(edr${MO[3]}_idw@EDRSH/31 - ${SPB})))"

fi

# temperature index
TI0="ti10min_${MO[0]}_v2r_org@TI_ORG"
TI1="ti10min_${MO[1]}_v2r_org@TI_ORG"

# cloud index
CLD0="hirs_${MO[0]}_10min@HIRS / 100 * ${HFTR}"
CLD1="hirs_${MO[1]}_10min@HIRS / 100 * ${HFTR}"
CLD2="hirs_${MO[2]}_10min@HIRS / 100 * ${HFTR}"

# cold stress index & heat stress index
CSI="( 1/(1+exp(${CPA}*( \
```

```

min(til0min_{$MO[0]}_v2r_min@CRU_MIN \
, til0min_{$MO[1]}_v2r_min@CRU_MIN \
, til0min_{$MO[2]}_v2r_min@CRU_MIN) \
+ ${CPB})) )"

HSI="( 1/(1+exp(${HPA}*( \
max(til0min_{$MO[1]}_v2r_max@CRU_MAX \
, til0min_{$MO[2]}_v2r_max@CRU_MAX \
, til0min_{$MO[3]}_v2r_max@CRU_MAX) \
- ${HPB}))) ) "

# rule statements
# Rule = TI AND (SI OR CI)
R1="${TI0} * (${SNW1}*${SNW2} + ${CLD1} \
- ${SNW1}*${SNW2}*${CLD1})"
R2="${TI1} * (${SNW2}*${SNW3} + ${CLD2} \
- ${SNW2}*${SNW3}*${CLD2})"

# map generation
g.remove rast=${TARGET}${HS[$H]}
r.mapcalc "${TARGET}${HS[$H]} = max(${R1} , ${R2}) * ${CSI} * ${HSI}"

# end of for loop
done

# merge NH and SH maps
g.remove rast=${TARGET}
r.patch input=${TARGET}${HS[0]},${TARGET}${HS[1]} output=${TARGET}

# export map in ArcGis format
r.out.arc input=${TARGET} output=/work/DwarfBunt/${TARGET}.asc dp=8

# end of script

```