Likely environments in which the non-indigenous freshwater diatom, *Didymosphenia geminata*, can survive, in New Zealand

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Prepared for

Biosecurity New Zealand

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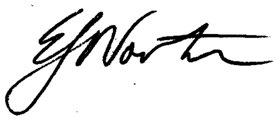

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Executive Summary

- As part of an assessment of the risk posed by the invasive diatom species *Didymosphenia geminata* to New Zealand's fresh waters, NIWA was requested by Biosecurity New Zealand to map likely environments in which the species may survive throughout New Zealand. The question was addressed using information on freshwater habitats in New Zealand provided by the New Zealand River Environment Classification (REC) and associated data.

- The main objective of the work was to map likely environments for *D. geminata* based on literature information on the species' environmental requirements and preferences. A further objective was to map likely environments for *D. geminata* based on the REC characteristics of the rivers in which the species is already present (the Mararoa and lower Waiau Rivers, Southland).

- In addition, for each analysis, Biosecurity New Zealand requested the distribution of likely environments within the bioregions defined in the Waters of National Importance (WONI) project.

- A review of available literature identified the following environmental characteristics as important in determining the distribution and growth of *D. geminata*: cool to warm temperature range, substrate and hydrologic stability, high light availability, moderate flow velocity, pH neutral or slightly alkaline. Insufficient information was found to determine whether any other water chemistry variables were critical.

- Values for eight variables associated with the REC were selected to describe the ideal environment of *D. geminata*, on the basis of the published information. A table was then made of the values of these variables applying to the entire REC (>650,000 river reaches). Multivariate statistical techniques were used to compute the environmental distances of 100 groups of similar river section types from the ideal environment.

- The REC network was then mapped, colour-coded to differentiate the 100 groups according to their distance from the ideal. This map could be interpreted as a stratification of the risk of establishment by *D. geminata* based on the best available information.

- The maps showed that areas having highest risk are Southland and Otago, Canterbury rivers on the eastern flanks of the Southern Alps, the Kaikoura Ranges, and the Central Volcanic Plateau, North Island. In addition scattered rivers in Fiordland, the West Coast, and the north-west Nelson region appeared to be high risk, as well as some rivers in the higher altitude areas of the North Island.

- Tables of the distribution of stream reaches in the WONI bioregions showed that the bioregions most affected were Southland, Clutha, Waitaki and Marlborough. Over 12% of the river reach lengths over the whole country fell into the 25% of environments (based on the 100 groups) closest to the "ideal" *D. geminata* environment.

- Overall, from the results of the analysis, it is estimated that over 50 percent of New Zealand's river area contains suitable habitat for the establishment of *D. geminata*, with the majority of suitable habitat in the South Island.

- This analysis is based on relatively sparse and often qualitative published information, and on averaged environmental information describing New Zealand rivers. Therefore, at the scale of a river section or less, the maps should not be interpreted too literally. However, on a broad scale, we believe that the stratification of risk corresponds well with our understanding of the environmental requirements of *D. geminata* reported from overseas, and its distribution on a global scale.

- Reaches with REC classes matching those in the affected rivers were mainly in the main stems of east coast, South Island, rivers, and in northern Southland and western Otago. In the North Island, less than 10 stream sections (in the Waipawa River catchment) matched those of the affected catchments in Southland in terms of REC characteristics. Because the mapped rivers were all main stem sections, they made up a very small proportion of the total number of river reaches in all WONI bioregions (<2%).

- The maps requested by Biosecurity New Zealand are included as A4 illustrations in this report, and can be provided as separate enlargements up to A0 size. This includes a map of the catchments currently affected by *D. geminata*, along with sightings of the species for which GPS coordinates are available.

- The data tables on which the maps are based will be provided in the requested format.

- Since completion of this analysis information has come to hand of *D. geminata* proliferating in warmers areas of the USA. This suggests that *D. geminata* may have a broader temperature tolerance than assumed, and the maps produced by the present analysis should therefore be interpreted as conservative. More information is required on the environmental conditions associated with these growths before any definite conclusions can be drawn.

1. Introduction

The introduced invasive diatom *Didymosphenia geminata* has been blooming in the lower Waiau and Mararoa Rivers, Southland, over the summer of 2004 / 05 and has been declared an "unwanted organism" by Biosecurity New Zealand. As part of the response to this new organism, Biosecurity New Zealand wish to evaluate the risk that *D. geminata* poses to New Zealand waterways as a whole. The key question is: if *D. geminata* were to be introduced to all waterways in New Zealand, where would it establish?

The aim of this project was to answer this question by using knowledge of the environmental requirements of *D. geminata* to map river environments in New Zealand in which it is likely to establish and survive. The analysis was undertaken using the New Zealand River Environmental Classification (REC) and associated data, to describe and stratify the environmental characteristics of New Zealand rivers in terms of their suitability for *D. geminata*.

In the project brief, Biosecurity New Zealand refers to *D. geminata* habitat rather than environment. We use the latter term in this report because the REC data describe general environmental conditions rather than specific habitat features. The data nevertheless are sufficiently detailed to differentiate a broad range of stream characteristics.

At the request of Biosecurity New Zealand, the analysis was in two parts. Objective 1 was to identify the range of REC classes in which *D. geminata* is currently surviving in the lower Waiau and Mararoa Rivers. These classes were to be mapped and tabulated nationally (and within the bioregions defined by the Waters of National Importance Project). Objective 2 was to use the available information on *D. geminata* requirements from the literature to identify the suite of REC classes that encompass the range in environmental conditions in which *D. geminata* will potentially become established. The potential distribution was to be mapped and tabulated nationally (and within the bioregions defined by the Waters of National Importance Project). This report focuses mainly on the second objective.

An additional objective was to stratify river reaches according to their suitability as environments for *D. geminata*. Thus every river reach in New Zealand would be assigned a level of risk of colonization and survival of *D. geminata*, ranging from no risk to high risk.

Biosecurity New Zealand also requested the following maps:

Map 1: showing river reaches with similar REC classes to the river reaches where *D. geminata* is known to be present in New Zealand.

Map 2: showing river reaches in New Zealand with similar REC classes corresponding to data on *D. geminata* environmental requirements from the literature.

Map 3: showing where *D. geminata* has been recorded to date in the Waiau and Mararoa Rivers, plus locations within the catchment (including all tributaries) that are environmentally similar to the sites of its current distribution.

Map 4: showing the risk stratification (with accompanying text on how the risk was calculated).

Below we describe the basis for our assessments of suitable environments, including a literature review, summary of environmental characteristics that we consider are important for *D. geminata*. In the literature search for *D. geminata* environmental preferences, factors were identified that could be represented better using the data associated with the REC, rather than the REC itself. Therefore we carried out the second objective using selected underlying continuous data, to produce a more refined stratification of environmental suitability than could be achieved by simply using the REC.

2. Literature review

As indicated in Kilroy (2004) there is little formally published data on the ecological requirements of *D. geminata*. However, some additional material has been acquired since that report was compiled. The information reviewed fell into five categories.

1. Taxonomic literature

Most diatom identification guides include information on the typical habitats of species, and ecological requirements. Generally this information is qualitative or based on the author's experience, and conveys broad impressions of habitat type and distributions.

2. Published information on periphyton communities

This includes published studies that include reference to *D. geminata* as a component of the periphyton, along with information on physical and chemical environmental conditions. Useful information in this category was found in Whitton (1984), in which the occurrence of *D. geminata* was described from several rivers in Europe, along with comprehensive information about their catchments. Two papers on algae in Turkey included reference to *D. geminata* (Kara & Sahin, 2001; Sahin 2002).

3. Published studies specifically focusing on *D. geminata*.

Older literature on *D. geminata* has generally focused on its morphology and fine structure. Only recently have ecological papers started appearing. To date these mostly refer to proliferations in central and eastern Europe (Kawecka & Sanecki 2003, Noga 2003, Subakov-Simic and Cvijan 2004), with one from Iceland (Jonsson et al. 2000).

4. Governmental internal reports and herbarium data

Two substantial reports were prepared on the 1990s blooms of *D. geminata* on Vancouver Island, Canada (Rieberger 1991; Sherbot and Bothwell 1993). In addition, the Montana Diatom Collection have a detailed entry on *D. geminata* including distribution information and associated environmental data.

5. Informal unpublished information

This is generally qualitative information obtained via personal communications or via the internet. Most of the information in this category was documented in Kilroy (2004) and provides qualitative confirmation (or otherwise) of published data. Additional useful information included distribution maps of *D. geminata* records in the UK and western North America, along with plots of pH and dissolved phosphorus versus *D. geminata* abundance from the UK. Several unpublished conference abstracts referred to *D. geminata*, but generally did not provide useful detail.

From each source we listed environmental characteristics, water chemistry data and other environmental information for locations where *D. geminata* has been reported. We also noted comments about places where it is *not* found – these are also relevant. Table 1 summarises the habitat characteristics identified from the literature as important in determining suitability for *D. geminata.* A commentary follows on each parameter, with reference to the literature and brief comments on New Zealand conditions.

2.1. Temperature

The traditional taxonomic literature conveys the clear impression that *D. geminata* is a cool-water species. For example, Krammer and Lange-Bertalot 1997 refer to *D. geminata* as occurring in boreal and alpine regions of Europe, Asia and North America, in cool, oligotrophic waters. Patrick & Reimer (1975) also mentioned a preference for cool waters. However, in a qualitative analysis of *D. geminata* distributions on Vancouver Island, Canada, Rieberger (1991) stated that "high water temperatures are favourable to the growth and expansion of *D. geminata*", and gave examples of expansion of *D. geminata* mats as water temperatures increased to 17 - 18°C. This corroborated the findings of Antoine & Benson-Evans (1986) who found *D. geminata* in higher-temperature localities in the River Wye system, Wales (though specific temperatures were not given). In a 12-month study in Turkey, Kara and Sahin (2003) found the highest density of *D. geminata* in mid-summer (July), with a water temperature of 17°C.

Other reports suggest rather lower temperatures associated with large growths. Reiberger (1991) also gave an example of the species "growing well" in a cooler stream (11°C). Noga (2003) reported that *D. geminata* was most abundant at a site in Poland where water temperatures from April to October ranged from 10 to 22°C; here the species attained greatest biomass in spring when the water temperature was reported as 12°C. In the River San, also in Poland, water temperatures of 11.5 and 14.6°C were recorded during massive growths of *D. geminata* (Kawecka and Sanecki 2003). Other reports from Europe state that the species attains its greatest densities in spring to late summer (e.g., Skulberg and Lillehammer 1984).

On a global scale *D. geminata* definitely seems to be confined to cooler areas. Published temperature ranges for regions where the species is found include: air temperatures 10 – 12°C, Norway (Skulberg & Lillehammer 1984), water temperatures of 0.1 – 22°C, Poland, R. San (Kaweck & Sanecki 2003), water temperatures of 7 – 20°C, Turkey, Degirmendere R. (Kara & Sahin 2001).

Evidence on a wider scale is seen from the distribution of *D. geminata* records in the UK (information from Martyn Kelly, UK, pers. comm.). Almost all records are from eastern Scotland – the coolest part of Britain – with other records from the hill areas in Wales and northern England. To date there are no records from lowland areas of southern Britain, though it is not known whether other environmental factors exclude the species from these areas. Similarly, records of *D. geminata* in western North America are all from mountainous areas. Further, in southerly locations, such as Colorado and California, all records are from areas >3000 m a.s.l. In Montana and Idaho, to the north, the species appears at lower altitudes (unpublished information, S. Spaulding, University of Colorado). (Note, however, that in spring 2003, a massive bloom of *D. geminata* was reported below Beaver Dam, Northwest Arkansas, which is a warmer and lower-lying area, though winters are typically cold. Refer to http://courses.missouristate.edu/rgr592f/Trout/Tailrace_algae_in_northwest_arkansas.htm for details.) *D. geminata* is common in the cool climate of Iceland (Jonsson *et al.* 2000). In a discussion of invasive diatom species, it was reported that "cold-water species like *D. geminata* seem to be absent in southern countries of Europe" (Luc Ector, France, unpublished conference abstract).

Several questions arise from these records and observations. Does *D. geminata* require cool temperatures at some stage in its life cycle (e.g., for establishing colonies), or has it failed to establish in warmer climates because it is out-competed by other taxa? Given that *D. geminata* grows prolifically in warmer waters (up to 18°C, Reiberger) is some factor other than temperature restricting its distribution to mountainous regions? Is the species limited by an upper temperature limit (>20°C) that would frequently be exceeded in warmer regions? Is prolific growth in cooler waters partly due to trophic effects, when reduced grazing activity permits enhanced algal growth (Kishi et al. 2005)? A further question is whether different strains of *D. geminata* might have different temperature tolerances or preferences. Morphologically different populations of the species are known to exist (Stoermer et al. 1986; Metzeltin and Lange-Bertalot 1995), which may also be ecologically different.

Some support for limitation by high temperatures arises from the observation that no live cells were found in *D. geminata* colonies in the laboratory after 48 hours at temperatures of 17 – 23°C, whereas colonies maintained at 14.6°C still contained many live cells after 9 days (Kilroy 2005).

That *D. geminata* appears to be confined to cool areas (mountainous or northern localities), yet within these localities attains its highest biomass at high water temperatures (up to 18°C) seems contradictory. Nevertheless, the evidence from its broad-scale distribution with respect to temperature is compelling. Therefore, for this analysis we assume that *D. geminata* does best in cooler regions.

Data available from New Zealand rivers show that in northern and eastern parts of the North Island, summer water temperatures in larger lowland rivers regularly exceed 23°C in summer and rarely fall below 8°C in winter. Higher-altitude rivers fall to about 5°C in winter and may exceed 20°C in summer. Farther south summer water temperatures tend to be lower and winter temperatures are almost always below 7°C. In the lower Waiau at Tuatapere, winter temperatures fall to 4 or 5°C, while in summer they occasionally exceed 20°C (NIWA data, National Water Quality Data Network).

2.2. Substrate and hydrologic stability

The literature is in general agreement that *D. geminata* requires stable conditions in order to establish and bloom. Substrate stability can arise in two main ways. First, large-sized substrate particles will remain in position in a higher range of water velocities than smaller particles. Large substrates are more likely to be encountered in catchments underlain by hard geological formations, rather than soft erodible rocks. Second, even with smaller-sized particles, substrates may be stable in rivers subjected to long periods of low flows, or to very stable flows. The latter conditions are typical of lake-fed rivers and regulated rivers below dams.

Substrate stability is not generally mentioned in the taxonomic literature, except indirectly by Cox (1996), who refers to its habitat in the UK as: "… particularly on damp rock faces in upland and northern areas". However, there are several references to this elsewhere. In the Glama River, Norway, Skulberg and Lillehammer (1984) quoted a typical habitat for *D. geminata* as "on boulder surfaces". Reiberger (1991) observed that in areas of the Puntledge River (Vancouver Island) with bedrock substrate, became covered with *D. geminata* earlier than other streams in the region.

There are numerous references in the literature to the connection between low and /or stable flows and *D. geminata* growth. In the River Tees, UK, Whitton and Crisp (1984) noted that large growths of *D. geminata* developed in the absence of scouring floods. The Glama River, Norway, where *D. geminata* is common, is lake-fed and regulated (Skulberg and Lillehammer 1984). In the River San, Poland, the first appearance of massive growths of *D. geminata* in the mid-1990s was coincident with exceptionally low rainfall and high summer temperatures in 1994 and 1995, and the lowest flow in a century in 1995. The largest growths were just below a dam (Kawecka & Sanecki, 2003). In their analysis of the *D. geminata* blooms on Vancouver Island, Canada, Sherbot and Bothwell (1993) noted that the affected rivers were all in volcanic /intrusive (granite) rock catchments, and that the area typically experiences low flows in summer and higher flows in winter, which appear to favour *D. geminata*. Reiberger (1991) reported "extensive coverage in years with no winter floods" and suggested that the blooms of the species in the area may have been related to a succession of below-average winter flows from 1985 to 1989. Conversely, on mainland British Columbia, most rivers typically have a regime of higher summer flows because of snowmelt, and low winter flows (Sherbot and Bothwell 1993). Many of the affected rivers on Vancouver Island were lake-fed, but not all (Reiberger 1991). In the western United States, the biggest growths have appeared in rivers below dams, and/or during periods of stable flow (e.g., Rapid Creek, South Dakota, S. Spaulding, University of Colorado, pers. comm.).

On the basis of published data we assume that in New Zealand, if other conditions are suitable, *D. geminata* will find the best opportunities for establishing and growing in lake-fed or regulated river systems in hard-rock catchments, which will tend to produce bouldery substrates. It would not be expected to establish on soft, erodible rock substrates such as mudstones and siltones. In addition, rivers on the east coast in particular are prone to long periods of low flows. If all other conditions are suitable, these rivers will also be suitable for *D. geminata*.

2.3. Light

D. geminata requires high light levels and does not grow well in shaded conditions. This was noted for the populations on Vancouver Island (Reiberger 1991), and Sherbot and Bothwell (1993) suggested that high levels of ultraviolet radiation may promote growth. Reiberger (1991) also observed that "north/south oriented reaches generally had limited cover of *D. geminata*, which may have been caused by reduced exposure to sunlight because of riparian vegetation." Distribution of *D. geminata* growth in the Wye River, Wales, was linked to high light intensities (Antoine and Benson-Evans 1986). The massive growths reported from the San River Poland were generally in a shallow part of the river "permitting the bottom to be well illuminated" (Kawecka and Sanecki 2003). Noga (2003) concluded that "shallow streams, with well-oxygenated water, a temperature which is not too high, and increased sunlight favour this diatom". No references could be located mentioning water clarity in relation to a requirement for high light levels. However, it seems reasonable to interpret a preference for shallow water in that context.

In New Zealand, a feature of many West Coast and Stewart Island streams is a high concentration of coloured dissolved organic matter, producing yellow to brown-coloured waters. It is not clear whether, all other factors being ideal, this would preclude *D. geminata* growth because of its light attenuation properties. However, Noga (2003) found that *D. geminata* was not observed in streams originating in peatlands, or those with brown-coloured waters, even though the species was found in clear-water tributaries of the same river system, just a few kilometers away. It is possible that water chemistry differences may also have contributed to a lack of *D. geminata* in these streams (see below).

In New Zealand, a high light requirement for *D. geminata* establishment and growth will exclude many small upland streams in forested catchments. However, numerous gravel-bed streams are highly exposed to sunlight, even in forested areas, and may be suitable environments, providing other conditions are favourable.

2.4. Flow velocity

Several references mention preference by *D. geminata* for relatively fast-flowing waters, although no formally published information quantifying the preferred velocities can be located. In the Glama River, Norway, Skulberg & Lillehammer

(1984) found *D. geminata* in the upper reaches of the rivers on boulders, facing into the current, and in rapids. Likewise, Heuff & Horkan (1984) recorded the species "on rocks in riffles" in the River Caragh, Ireland. Noga (2003) reported finds of *D. geminata* in tributaries on only one side of the Czarna-Orawa River, Poland, where the streams had cooler water, faster current, and rocky bottoms. Reiberger (1991) made several observations that *D. geminata* did not grow in areas with extremely fast or extremely slow currents.

In New Zealand, a preference for faster currents would preclude many lowland streams, or lowland reaches of larger rivers. Such streams are also likely to be unfavourable environments for *D. geminata* for other reasons.

2.5. Water chemistry: pH

The only reasonably established water chemistry requirement for *D. geminata* relates to pH. pH "preferences" in diatoms have long been recognized, and apply to many species (Batterbee et al. 1999). Most literature located stated a pH of between 7 and 8.5 as the optimal range for *D. geminata* (R. San, Poland, 7.4 to 9.2, Kawecka & Sanecki 2003; Degirmedere R., Turkey, 7.8, Kara & Sahin 2001; Poland, Czarna-Orawa River, 7.5-8.9, Noga 2003; 7 Montana Diatom Collection diatom collection data; Vancouver Island, 7.2 – 7.7, Sherbot and Bothwell 1993; UK rivers, mean ~7.7, unpublished data, Martyn Kelly, UK).

Most of the larger rivers in New Zealand have a mean pH within the range 7.1 to 8.3. Some streams in Hawkes Bay and the central volcanic area are more alkaline (up to 8.8) (NIWA data). All these would fall within the range for *D. geminata*. Exceptions are small West Coast streams that are acidic due to a high humic acid content leached from forested or peat catchments (pH as low as 4, Collier and Winterbourn 1990). This suggests that brown-water streams are probably unsuitable habitat for *D. geminata* both on the basis of light penetration (see section above) and pH, although there may be exceptions where the humic acid content is low.

2.6. Water chemistry: nutrients

Some older taxonomic texts have been reported in the literature as implying that *D. geminata* is indicative of clean, low-nutrient waters (Kawecka and Sanecki 2003). Patrick and Reimer (1966) stated: "prefers cool water of low conductivity." Krammer & Lange-Bertalot (1997) stated that the species is found "only in cold oligotrophic waters of the Alps, though ranging from low to high electrolyte content". While its distribution mainly in mountainous areas suggests that this may be an accurate assessment, its recent expansion in Eastern Europe points to a wider tolerance of nutrient conditions. Kawecka and Sanecki (2003) provided comprehensive evidence of a wider ecological range for this species than has been assumed to date. The limited information located in the literature on nutrient levels associated with *D. geminata* suggests that the species can thrive with very low nutrient levels, but is not inhibited by elevated levels. For dissolved phosphorus, several sources quote low concentrations (0.002 to 0.01 mg/l) (Skulberg and Lillehammer 1984, Montana Diatom Collection herbarium data), whereas others give much higher ranges, up to 0.1 mg/l (Kawecka and Sanecki 2003; Noga 2003, M. Kelly, UK, pers. comm.). Dissolved reactive phosphorus measured in New Zealand rivers varies from 0.001 to 0.075 mg/l. Highest values have been recorded in the North Island (e.g., Waikato, Tarawera and Manawatu Rivers. South Island rivers are generally at the low end of the range (means over 14 years in 78 larger river, NIWA data).

Dissolved nitrate values associated with *D. geminata* growth similarly span a wide range, from 0.065 mg/l (Skulberg and Lillehammer 1984) to 0.47 mg/l (Noga 2003). Interestingly, Kawecka and Sanecki (2003) report a much lower value for NO_3 in the San River during the time of *D. geminata* blooms, than the stated range for the affected site (0.007 mg/l versus 0.52 – 2.76 mg/l), suggesting uptake of NO_3 by the growths. Sherbot and Bothwell (1993) found significant differences in nitrate/nitrite levels between catchments affected by *D. geminata* blooms on Vancouver Island, but did not find any pattern distinguishing affected from unaffected rivers. Levels in general were very low (0.025 to 0.055 mg/l).

Recently Subakov-Simic and Cvijan (2004) reported regular findings of *D. geminata* in the Tisa River in Serbia, in moderately polluted, low-clarity waters, containing high levels of dissolved nitrates (up to 2 mg/l). However, since the live cells were found in the plankton rather than the benthos, it is suspected that these occurrences originated from massive blooms upstream in the San River and may not represent establishment and growth of the species in this environment.

The New Zealand mean values for dissolved nitrate in general fall within the range recorded overseas in rivers with *D. geminata*. Some of the large lowland rivers have relatively high concentrations (e.g., Waihou – 1.01; Waingongoro – 1.8; Mataura – 1.1 mg/l NO_3).

The wide range of dissolved nutrients associated with large growths of *D. geminata* suggest that nutrient levels cannot be used to determine environments favourable for this species.

2.7. Water chemistry: other factors

There is limited information in the literature on other chemical factors that may influence the distribution of *D. geminata*. It has been suggested that the species does well where there is some calcium (E. Haworth, Freshwater Biologocal Association, UK, pers. comm.) Calcium concentrations reported in association with *D. geminata* blooms range from 2.9 to 40 mg/l. Values for New Zealand rivers generally lie within this range, with the exception of some North Island, east coast rivers draining calcareous catchments, in which values can be higher (e.g., Waipoa River, range 45 – 70 mg/l) We therefore assume at this stage that calcium concentrations are not critical in determining where *D. geminata* might grow. Measures of conductivity are similarly broad.

Table 1: Summary of ecological requirements of *D. geminata*, determined from a literature review

Parameter	Value / range	References
Temperature	Generally 11.5 – 14.6°C reported during blooms, but possibly increasing cover as temperature increases beyond this (e.g., 17-18°C*). Blooms most abundant in summer BUT cool temperature at some stage: almost all rivers have a temp. range from ~6 to 20+	Kawecka & Sanecki 2003; Sherbot & Bothwell 1993; *Reiberger 1991
Flow regime characteristics	Long periods of low flow or flow stability (leads to blooms) Lake-fed rivers Rivers below dams	Antoine & Benson-Evans 1986 Rieberger 1991 Kawecka & Sanecki 2003; Whitton & Crisp 1984
Substrate type	Stable Boulders, bedrock, rock walls	Skulberg & Lillehammer 1984; Cox 1997
	Hard rock	Sherbot & Bothwell 1993
Flow velocity	"Fast-flowing" (riffles, rapids) Tends to be excluded from areas of very slow-moving and very fast-moving (>1 m/s) water	Heuff & Horkan 1984 Sherbot & Bothwell 1993
Light	High exposure to sunlight (not shaded)	Rieberger 1991; Kawecka & Sanecki 2003
Water clarity	Requires high light intensities (= clear water)	implied from light req.
Water colour	Probably clear; not in brown-coloured waters fed from peatlands	Noga 2003
Geology	Hard rocks: volcanic/ intrusive Non-calcareous	Sherbot & Bothwell 1993
PH	Average of about 7.7, where blooms present pH of 6.9 reported	Multiple references
Conductivity	Wide range, often in 30 – 70 range But can be >250	Multiple references
Phosphate (mg/l)	Often around 0.002 But can go to 0.01	Multiple references
Nitrate (mg/l)	Wide range 0.007 to 0.32	Multiple references
Calcium (mg/l)	Wide range 4 to 45	Multiple references

3. Methods

3.1. The River Environment Classification (REC)

The framework that we used to develop potential distributions of *D. geminata* was the New Zealand River Environment Classification (REC). The REC was developed by NIWA as a tool to aid water resources management in New Zealand. REC classifies individual sections of New Zealand's river networks on the basis of a hierarchy of controlling factors, including climate, topography, geology and land cover of the catchment of each section, and attributes of the section itself. The system is based on a GIS layer that defines river section with a mean unit size of approximately 1 km. Snelder & Biggs (2002) provide full description of the system and a brief account follows.

The REC represents the network of New Zealand's rivers at a 1:50 000 scale. Individual sections are defined by their confluences with tributaries at both their upstream and downstream ends. Thus, sections are homogenous units with respect to flow magnitude and the constituents of that flow. River environments are described in terms of six factors, which are arranged in order of their overall importance in determining the river environment. The factors range from the broad-scale overarching influence of climate, to the relatively small-scale (~1 km) description of the slope of an individual river section. For the purposes of classification, each factor is divided into categories, which have been assigned to every reach section in New Zealand. The factors are listed in Table 2, in order of level in the hierarchy, along with the individual categories for each factor.

A database of 'mapping characteristics' was used to map the REC classes. Mapping characteristics were chosen to represent each factor and were evaluated for each section in the network. Criteria were then applied to determine category membership. For example, mean annual rainfall and temperature were used as mapping characteristics for the factor Climate. Thus, the database contains data describing the mean rainfall and temperature of the catchment of every section of the river network. Particular criteria were applied to assign every section of the network to a Climate category. For example, sections were assigned to the "Cool" category if their mean annual air temperature was less than 12^{o}C. The complete list of mapping characteristics and category criteria are shown in Table 2. The assignment process produced a simpler database where each network section is assigned to a category for each level of the classification. The class at any level of the REC hierarchy is simply the concatenation (successive joining) of categories for each level in the classification hierarchy. The classification for each section is attached, as a set of attributes, to the polyline that represents the network section, and the entire network and classification is saved as a GIS map layer. Classes are mapped by displaying sections by class at any hierarchical level required.

Although the basic REC is a categorical system, it is underlain by the continuous mapping characteristic data. This REC data have been supplemented by other data as part of the development of Freshwater Environments of New Zealand (FWENZ) for Department of Conservation (Snelder et al. 2005). This allows us to undertake additional analyses on the river sections defined within the REC.

Table 2: Summary of categories, mapping characteristics and category membership criteria for application of REC to New Zealand rivers.

Classification level	Classes	Notation	Mapping characteristics	Category assignment criteria
1. Climate	Warm Extremely Wet Warm Wet Warm Dry Cool Extremely Wet Cool Wet Cool Dry	WX WW WD CX CW CD	Mean annual precipitation, mean annual potential evapotranspiration, and mean annual temperature.	Warm: mean annual temperature ≥ 12°C Cool: mean annual temperature < 12°C Extremely Wet: mean annual effective precipitation ≥ 1500 mm Wet: 500 > mean annual effective precipitation < 1500 mm Dry: mean annual effective precipitation ≤ 500mm
2. Source of Flow	Glacial mountain Mountain Hill Low Elevation Lake	GM M H L Lk	Catchment rainfall volume in elevation categories, lake influence index	GM: Permanent ice cover in catchment > 1.5% M: > 50% annual rainfall volume above 1000m ASL H: 50% rainfall volume between 400 and 100m ASL L: 50% rainfall below 400 m ASL Lk: Lake influence index > 0.033
3. Geology	Alluvium Hard Sedimentary Soft Sedimentary Volcanic Basic Volcanic Acidic Plutonic	Al HS SS Vb Va Pl	Proportions of each geological category in section catchment.	Class = the spatially dominant geology category unless combined soft sedimentary geological categories exceed 25% of catchment area, in which case class = SS.
4. Land Cover	Bare Indigenous Forest Pasture Tussock Scrub Exotic Forest Wetland Urban	B IF P T S EF W U	Proportions of each land cover category in section catchment.	Class = the spatially dominant land cover category unless P exceed 25% of catchment area, in which case class = P, or unless U exceed 15% of catchment area, in which case class = U
5. Network Position	Low Order Middle Order High Order	LO MO HO	Stream order of network section	Stream order 1 and 2 Stream order 3 and 4 Stream order ≥ 5
6. Valley Landform	High Gradient Medium Gradient Low Gradient	HG MG LG	Valley slope of section based on Euclidian length.	Valley slope > 0.04 0.02 ≥ Valley slope ≥ 0.04 Valley slope < 0.02

3.2. Literature-based analysis

3.2.1. Development of risk stratification

Because information from the literature review identified factors that could be better discriminated using the continuous data underlying the REC classification, supplemented with data from FWENZ, we used a multivariate analysis technique to generate a reach classification for the map based on literature data. The classification was then converted to a risk stratification by ordering the classes according to their overall similarity to a set of predetermined “ideal environmental characteristics” for *D. geminata*. This approach means that the Maps 2 and 4 requested by Biosecurity New Zealand have been merged.

Using this approach, development of the risk stratification was a five-step process, as described below.

1. Selection of relevant variables

Data for over 100 variables are available for every stream section in the REC. These comprise mainly climate, topographical, geological and land cover information either related to the stream section itself, or to the stream’s upstream catchment. All variables were considered in light of the literature review and a subset of eight environmental variables were selected that we considered best represented the factors that are critical to the distribution of *D. geminata*. Weightings were applied to variables as appropriate. The selected variables are listed in Table 3 and our justification for each selection follows.

Table 3: Variables selected for inclusion in the analysis of New Zealand rivers for likely environments for *D. geminata* establishment and growth

Variable label	Weighting	Description
UsAvTWarm	x4	Mean January air temperature in the upstream catchment
UsLake	x2	Lake index (an index describing the level of lake influence for each network secton)
UsHard	x1	An index describing the average geological hardness of the catchment (scale 0 to 5)
usRainday25	x1	Average number of days per month on which catchment rainfall exceeds 25 mm
SegSlope	x1	Average slope of the stream section
SegShade	x1	Estimate of degree of shading within the stream section (scale 0 to 1)
UsPeat	x1	% of catchment with peat soils
UsGlacial	x1	% of catchment covered by glacier

usAvTWarm is the average daily air temperature of the catchment for January. The data originated from the Land Environments of New Zealand (LENZ) database (Leathwick et al. 2003) and was processed for application to the catchment of every river section in the REC. We used air temperature as a surrogate for water temperature because there is insufficient water temperature data to reliably extrapolate values to the whole country. In addition, the relationship between air and water temperature can be complex, and national scale models to derive the latter have produced inconsistent results (Wild et al. 2005).

We considered the use of air temperatures a more reliable approach, on the assumption that mean catchment air temperature was a reasonable reflection of the water temperature at the selected section (the most downstream section in the catchment). The average for the warmest month was selected because it seems most likely that *D. geminata* is limited by high temperatures, rather than showing a preference for low temperatures (Section 2.1). Use of the maximum mean temperature over the year enables selection of upper temperature thresholds in order to discriminate suitable from unsuitable environments. Because temperature is considered important in determining the large-scale distribution of *D. geminata*, this variable was quadruple-weighted in the cluster analysis based on evidence for the need to weight critical variables provided by Snelder et al (2005).

usLake indicates the degree to which a river section is influenced by lake-fed waters, on a scale of 0 to 1. It is calculated as the ratio of rainfall within lake subcatchments to rainfall in the whole catchment (Wild et al. 2005). Within the basic REC, a lake index of >0.033 was the criterion for assigning a lake source-of-flow (Table 2). The literature review suggested that *D. geminata* does particularly well in lake-fed rivers. Such rivers tend to be less flashy and flood-prone than runoff-fed systems, and therefore provide the stability that favours growth of this diatom. Regulated rivers below dams may be extreme examples of stable systems and have been reported to support massive growths of *D. geminata* (Section 2). Because of the stabilizing effect of lake outflows, we assume that this factor leads to very favourable growth conditions for *D. geminata*. The variable was therefore given double weighting in the cluster analysis.

usHard is an index of the proportion of hard rock in a catchment that is derived from a 5-step scale of rock hardness adopted by the LENZ. We assume that higher proportions of hard rock in a catchment are associated with the larger, harder and more stable river substrates that favour the establishment and growth of *D. geminata*. Catchments with a low hardness index are likely to contain easily erodible soft rocks such as the mudstones and siltsones prevalent in parts of the North Island (Leathwick et al. 2003). We assume that rivers with such catchments will tend to have fine substrates, and may also tend to have naturally turbid water, which is not ideal for *D. geminata* because of its requirement for high light levels.

usRainday25, the mean number of days per month when rainfall exceeds 25 mm, is one of a series of variables developed to represent flow variability (Wild et al. 2005). The 25 mm criterion is the median of seven available values ranging from 10 to 200 mm, and we considered this to be the optimum choice for representing flow variability over the whole range of catchments in New Zealand. The data on which the GIS surface was based originated from almost 1000 rainfall recording sites, which ranged in the mean number of days per month with greater than 25 mm of rainfall from 0.07 to 6.8. The highest values of usRainday25 were recorded in the wetter areas of the West Coast and the lowest are suited on the east coast of both islands. We assume low values of this parameter indicate rivers that are prone to long periods of low, steady flows, and high values indicate rivers that are more flood-prone, with fewer periods of extended low flow. Since *D. geminata* appears to require stable water flows to establish and to attain high biomass, then low values of usRainday25 will be favourable.

segSlope, the average slope of the stream section, is calculated from the REC raw data on a scale 0 to 1. *D. geminata* appears to do best in moderately fast-flowing water, but is reported not to establish in very fast-flowing or very slow-flowing water (Section 2). For the purposes of this analysis, we assumed that favourable environments for *D. geminata* will be sloping, but the slope may be quite low (around 0.01). Such rivers may comprise alternating riffles and runs, with the riffles providing the best habitat for *D. geminata*. Our analysis showed that streams with very steep slopes (>0.15) often had high shade (>0.5) and so tended to be less favourable for *D. geminata* for both reasons.

segShade is an estimate of the shading within the reach section, on a scale of 0 (completely open) to 1 (fully shaded). This was derived from the estimated flow in a section (using flow to estimate river-bed width), and catchment vegetation from the New Zealand Land Cover database (LCDB) (Wild et al. 2005). Since high exposure to sunlight is favourable for *D. geminata* growth, shade less than 0.1 was considered most suitable.

usPeat is the proportion of the catchment overlain by peat soils. These data were derived from the New Zealand Land Resources Inventory (LRI). The variable ranges from 0 to 1. The largest peat deposits occur in Southland, Westland, Waikato and Northland (Leathwick et al. 2003). The presence of a large proportion of peat in a catchment is likely to result in tannin-stained waters that may also be acidic (from humic acids). *D. geminata* is almost invariably recorded in neutral to slightly alkaline waters. Therefore we assume that the acidity associated with waters from peat-rich areas will be unfavourable for *D. geminata* growth. In addition, light attenuation by the yellow-brown stain of the water may mean that the light climate in these waters is also unfavourable.

usGlacial is the proportion of a catchment covered by glaciers. This data was derived from the LRI and has a range 0 to 100%. Streams fed from glacial outflow generally contain high concentrations of glacial ‘flour’ - very fine rock particles formed by the grinding of rocks as the glacier moves downstream. Glacial flour gives the water a milky appearance and glacial streams are characterized by poor water clarity. Low water clarity may be a feature throughout the main stem rivers as far as the coast where there are large areas of glaciers in the headwaters. No reference to glacier-affected waters was located in the literature; however, we assume that the low water clarity associated with glacial rivers is not favourable for *D. geminata* growth, in view of the species’ reported high light requirement.

A data table was compiled from the REC mapping characteristics data and the FWENZ database that contained each of the eight variables listed above for every river section in New Zealand (>650,000 sections). All data were used directly without transformation in the classification procedure.

2. Reduction of REC stream network data

A cluster analysis was performed on the environmental data to group sections according to their environmental similarity (i.e., their similarity with respect to the environmental variables). This analysis produced 100 groups (clusters) of sections with similar environmental characteristics. Mean values for the variables were calculated within each group. A complete discussion of the clustering procedure is contained in Appendix 1.

3. Definition of the ideal *D. geminata* environment

Because no single existing group stood out as representing the "ideal" for growth of *D. geminata*, we added an extra group to the 100 clusters. This comprised what we considered to be the best combination of environmental conditions for *D. geminata* (based on the ranges of the 8 variables that are described in Table 3 and based on published information. Justification follows for our selection of "ideal" values for each of the eight selected variables.

Temperature: Definition of an "ideal" temperature, the parameter we considered most critical in determining *D. geminata* distribution, presented some difficulty. This was because of a lack of water temperature data, and also a rather wide range of temperatures reported to be associated with *D. geminata* blooms. While we believe usAvTWarm provides an acceptable national scale surrogate for water temperature, we have not made any attempt to confirm this with correlative studies. Some data exist to explore this, however it is a reasonably large task and falls outside the scope of this contract. At this stage, the only useful information available is monthly water temperature readings at Tuatapere in the lower Waiau (NIWA data, over 12 years), which can be compared to usAvTWarm values throughout the river. Therefore, although this section of the analysis was intended to be based purely on published data, use of lower Waiau data was our only option for assessing an "ideal" temperature for *D. geminata*. Recorded January water temperatures in lower Waiau at Tuatapere range from 13.5 to 21.2°C, (1990 to 2003, mean 16.8°C). Heavy growth of *D. geminata* has been reported overseas in temperatures ranging from 11.4 to 18°C, suggesting a wide optimal range (Section 2), possibly slightly cooler than the lower reaches of the lower Waiau. usAvTWarm in the *D. geminata*-affected reaches in the Mararoa – lower Waiau mainstem ranges from 10.2 to 11.8°C. On the grounds that water temperatures in the lower catchments cover a warmer range than those associated with *D. geminata* blooms overseas, we selected usAvTWarm of 10°C as the optimum for *D. geminata*.

Lake: From the literature it is clear that lake-fed rivers provide a particularly good environment for *D. geminata*. We selected an ideal value of 0.6 rather than 1 on the grounds that 0.6 indicates a very pronounced lake influence. This value (rather than a higher one) would allow rivers with a lower (but still significant) lake influence to rank as suitable for *D. geminata*, if other factors were favourable.

Hardness: A hardness value of 4 was selected. The relatively high value reflects the requirement by *D. geminata* for stable substrate for establishment, and ensured that stream sections in softer-rock areas would be well separated from the ideal conditions, unless several other factors were also suitable.

Rainfall: The mean value of usRainday25 in the 100 groups ranged from 0 to 3.3 (mean 1.31) (Appendix 2). A relatively low value would be ideal for *D. geminata*. Again a value >0 was chosen so that values both above and below the "ideal" would be computed as being close to the most suitable conditions. Many east coast rivers – in the low-rainfall parts of New Zealand that are often subject to periods of low flows – have recorded values for this variable up to 0.75. We selected an ideal of 0.5.

Slope: A slope of 1% (segSlope = 0.01) was selected as the ideal for *D. geminata*, within a range from 0 to 0.31 (mean 0.07) for the 100 groups. Slopes around this value represent reaches that are likely to contain a sequence of riffles and runs.

Shade: In the 100 groups produced in the cluster analysis, the stream section shade index ranged from 0.0013 to 0.78 (mean 0.41). The ideal value of segShade was set at 0.04 rather than 0, to avoid placing too great a distance between the "ideal" and sites that had a shade index up to 0.1, which still indicates high exposure to light in most of the stream bed.

Peat: The distribution of usPeat mean values over the 100 groups of reaches was extremely skewed, Ninety of the groups had values of <0.02, while the remaining 10 had relatively high values (0.13 to 0.89). This variable was set at 0 on the grounds that all the low values would barely influence the similarity analysis, and only the very high values would be likely to affect water colour or pH sufficiently to influence environmental suitability for *D. geminata*.

Glacial: The usGlacial variable was set to 0, for the same reason as usPeat.

4. Calculation of similarities to the ideal environment

The next step was to use the mean environmental character of each of the 100 New Zealand clusters to describe its environmental similarity to our ideal combination of conditions. This allowed all clusters to be ranked (stratified) from most to least suitable for *D. geminata* (relative to the ideal). We used the Gower metric to measure environmental similarity between sites. This is a range standardised city block

(Manhattan) type similarity measure that effectively gives each variable equal weighting (Sneath and Sokal 1973). We made additional inclusions of the weighted variables in the calculations (according to their weighting factor, Table 3) to ensure that these have a greater leverage in the outcome.

5. Assessment of risk applicable to New Zealand stream environments

The ranking was then applied to all the sections in the network based on the similarity of each of the 100 clusters to the most suitable environmental conditions for *D. geminata*. The ranked groups thus represented river sections spanning most suitable to least suitable environmental conditions for *D. geminata*. To produce the "stratification of risk" (Map 4), the entire network was mapped using the REC framework, allowing a map of relative suitability for *D. geminata* to be shown in terms of a colour scheme. The maps can be interpreted as a stratification of the risk of colonization by *D. geminata*.

3.3. REC-based mapping

Using the REC it is possible to automatically generate a list of all river sections downstream of any selected upstream section. The infestation of *D. geminata* is known to start in the Mararoa River, about 200 m upstream of the Kiwi Burn bridge and has been reported along almost the entire length of the Mararoa and lower Waiau Rivers, to at least as far downstream as Clifden (approx. 10 km upstream of the tidal influence). A complete list was produced of REC classes (at the 6th level of the classification) to the outlet of the lower Waiau River at the coast. The classes were then grouped, and ranked according to their frequency of occurrence.

A map (Map 1 requested by Biosecurity New Zealand) was generated of all occurrences of these classes throughout New Zealand, colour-coded according to their frequency within the affected catchments.

4. Results

4.1. Literature-based analysis

4.1.1. Stratification of risk

Mean values for the eight selected variables in the 100 clusters produced in the cluster analysis are shown in Appendix 2. These groups were mapped, with colour-coding corresponding to their distance from the "ideal" group. In Figure 1, red reaches are

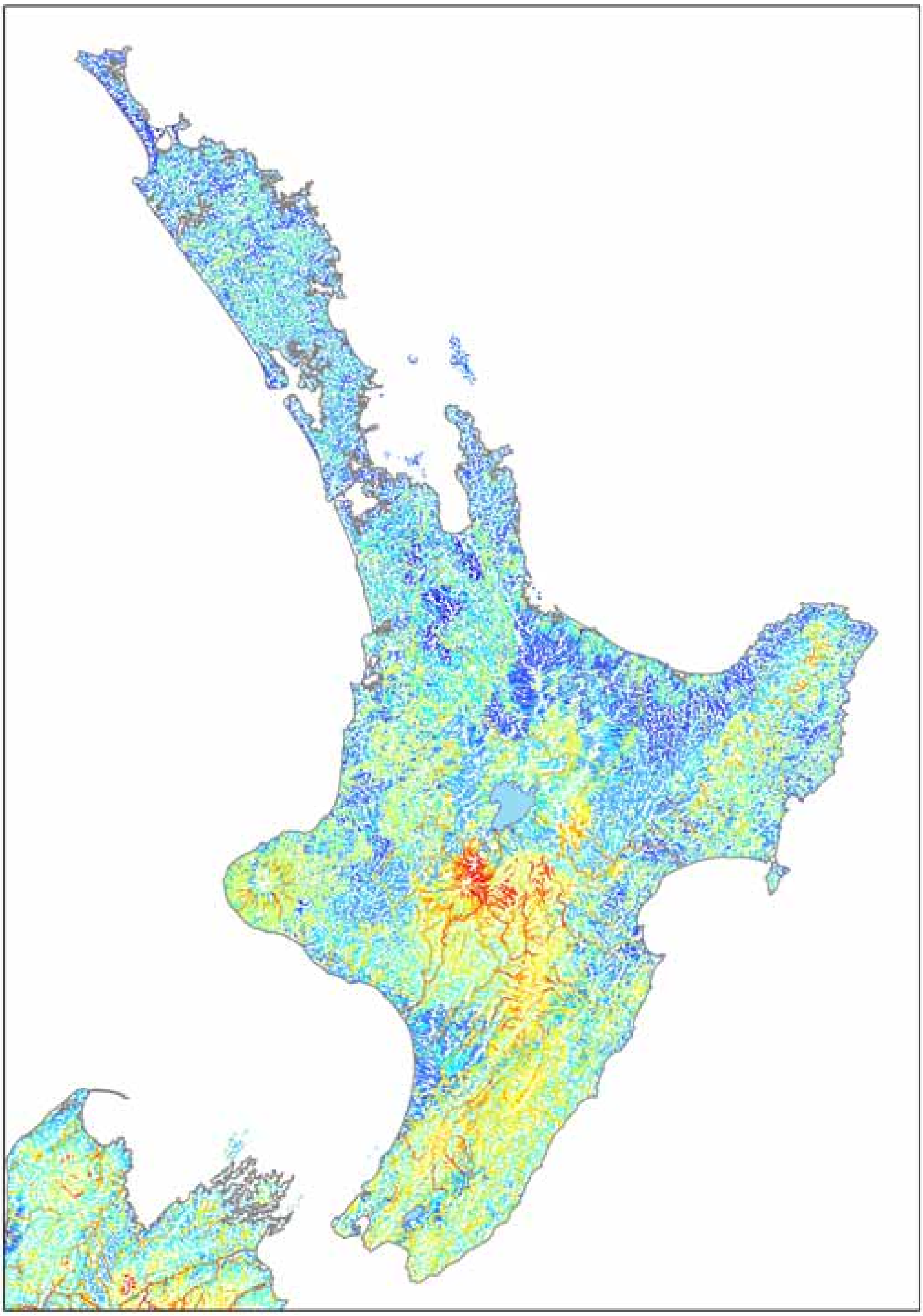

Figure 1. Stratification of risk of establishment and blooming of *D. geminata* based on the environmental similarity to the ideal conditions defined using the eight environmental variables shown in Table 3. The colour scheme is based on continuous variation in colour from red (very similar environment to the ideal) to dark blue (least similar environment to the ideal). (a) North Island.

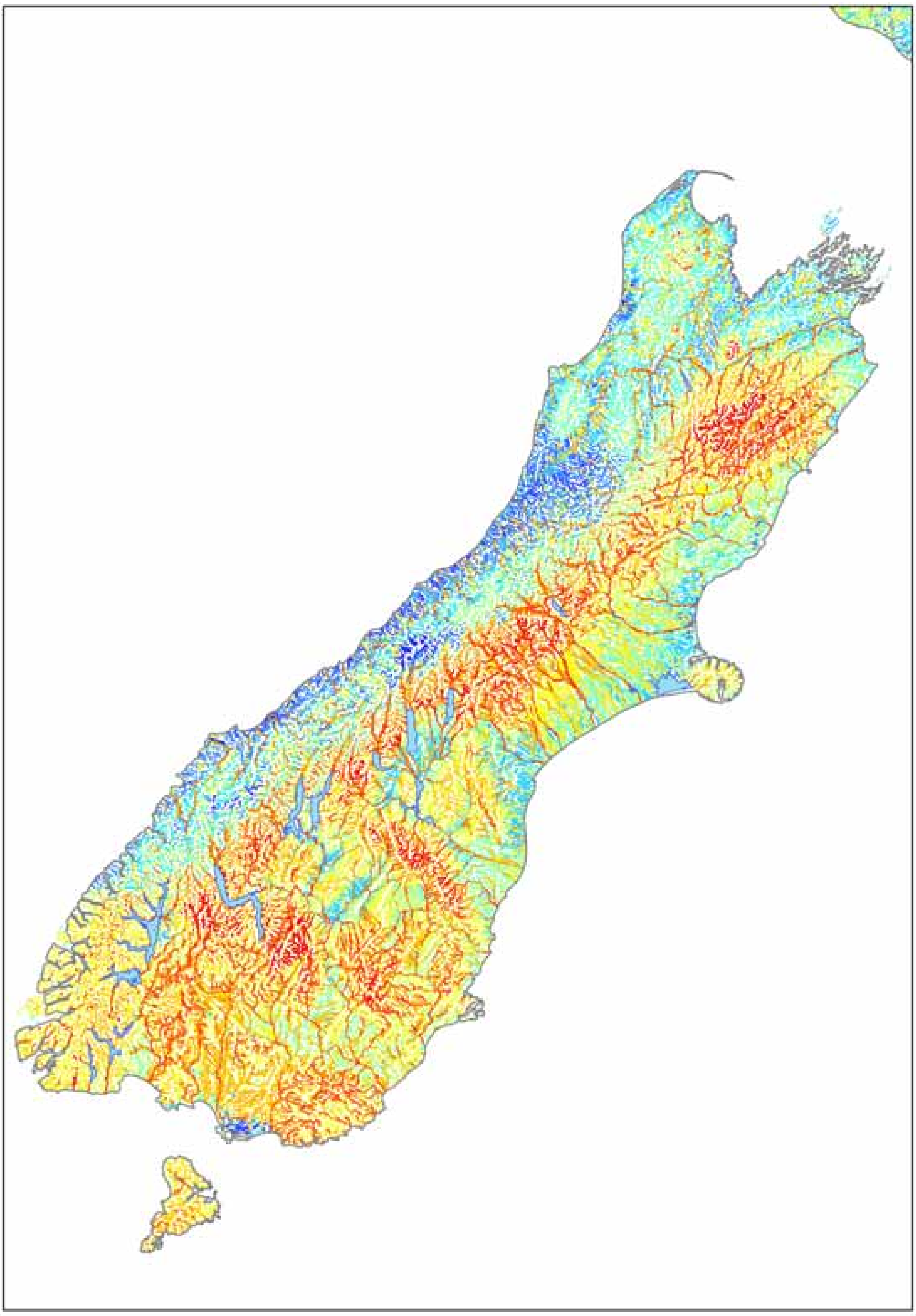

Figure 1. (b) South Island.

those closest to the ideal group, and blue reaches are those separated by the greatest distances. This can be interpreted as red areas being most at risk from colonization by *D. geminata* (according to our assessment of literature information) and blue areas as least at risk.

Table 4 shows the distribution of river reaches in different risk bands in the 29 WONI bioregions. For this tabulation, we separated the 100 groups arbitrarily into 4 subgroups on the basis of distance from our "ideal" environment. Group boundaries are taken at one quarter of the distance between the closest group to the ideal and the most distant group.

Given that at this stage, *D. geminata* is established only in the main stem of the lower Waiau and Mararoa Rivers[1], it is of interest to apply the risk stratification to the REC data for high order streams only. The percentages of stream lengths in each of the 4 subgroups, by WONI bioregion, are shown in Table 5.

4.2. REC-based mapping

A total of 245 REC sections made up the currently affected sections of the Mararoa and lower Waiau Rivers. These comprised 10 REC classes (at the sixth; most detailed level of the REC) (Table 6). The reaches are mapped with colour codes according to the abundance of each reach type in the affected rivers (Figure 2).

Figure 2 shows that the most abundant REC class in the currently affected reaches is confined to the lower Waiau River and several adjacent rivers in the same region. This is largely a function of the combination of a cool, extremely wet climate, and Plutonic geology. The rarer REC classes were almost all in the Mararoa River. These classes also occurred in a range of South Island east coast rivers, including much of the Clutha and Waitaki Rivers, portions of the Orari, Ashburton, Selwyn, Waimakariri and Ashley Rivers, much of the Clarence River and parts of some smaller rivers in the north-east. Close to the affected catchments, the upper reaches of the Oreti and Mataura were included, as well as the Von and parts of the Shotover and Kawarau. Only one river in the North Island had matching REC classification, within the Waipawa catchment, south of Hawkes Bay.

The occurrence of these REC classes (combined) within Waters of National Importance (WONI) project bioregions is shown in Table 7, as percentage of the total

[1] Since the present analysis was completed, *D. geminata* has been observed in two tributaries of the lower Waiau / Mararoa system, although very close to the main stem.

Table 4: Distribution of assessed risk of colonisation by *D. geminata* within the 29 bioregions defined in the Waters of National Importance project, expressed as a percentage of total length of river reaches in each region in four bands of risk. The risk bands are defined by their environmental distance from the "ideal" *D. geminata* environment by dividing the range of distances equally into four. Total percentages for North Island, South Island, and all New Zealand are also given.

	Distance from "ideal" *D. geminata* environment (%)			
WONI bioregion	< 0.215	0.215 – 0.295	0.296 – 0.376	>0.38
South Island				
Banks Peninsula	4.2	72.7	23.0	0.0
Canterbury	18.5	53.9	27.6	0.0
Clutha	27.0	63.6	9.1	0.3
Fiordland	14.5	66.1	19.2	0.1
Grey-Buller	8.6	21.3	70.1	0.0
Marlborough	22.8	46.3	30.9	0.0
Motueka-Nelson	8.3	19.5	72.3	0.0
Northwest Nelson-Paparoa	5.8	19.7	74.4	0.2
Otago Peninsula	4.3	95.7	0.0	0.0
Southland	28.2	68.5	3.4	0.0
Stewart Island	8.6	91.2	0.2	0.0
Taieri	16.8	83.1	0.1	0.0
Waitaki	24.1	65.6	9.1	1.2
Westland	6.2	24.8	65.2	3.7
South Island total	**19.3**	**54.1**	**26.1**	**0.5**
North Island				
Auckland	0.0	9.5	89.5	1.0
Bay of Plenty	1.2	21.2	77.0	0.6
Coromandel	0.3	9.1	90.4	0.2
East Cape	1.6	21.1	77.2	0.0
Hawkes Bay	5.9	30.7	63.3	0.1
Manawatu-Wairarapa	5.1	46.7	47.9	0.3
Mokau	0.0	30.1	69.9	0.0
Northland - eastern	0.0	18.3	79.4	2.3
Northland - northern	0.0	2.6	85.1	12.3
Northland - western	0.0	21.9	77.7	0.5
Palliser-Kidnappers	0.0	42.2	57.8	0.0
Taranaki	4.8	42.8	51.8	0.6
Waikato	2.5	42.4	52.6	2.5
Wanganui-Rangitikei	6.8	39.0	54.2	0.0
Wellington	4.5	42.3	52.9	0.2
North Island total	**3.0**	**33.1**	**63.1**	**0.8**
All NZ Grand Total	**12.4**	**45.2**	**41.8**	**0.6**

Table 5: **As Table 4, but with percentages calculated after selecting only high-order stream sections from the REC database. (Zeroes for all four distance groups indicates that there are no high-order streams in the bioregion.)**

	Distance from "ideal" *D. geminata* environment (%)			
WONI bioregion	< 0.215	0.215 – 0.295	0.296 – 0.376	>0.38
South Island				
Banks Peninsula	0.0	0.0	100.0	0.0
Canterbury	68.9	30.3	0.8	0.0
Clutha	88.1	11.3	0.6	0.0
Fiordland	89.2	10.8	0.0	0.0
Grey-Buller	68.1	28.9	3.1	0.0
Marlborough	83.8	15.3	0.9	0.0
Motueka-Nelson	79.3	19.9	0.8	0.0
Northwest Nelson-Paparoa	63.7	33.5	2.8	0.0
Otago Peninsula	0.0	0.0	0.0	0.0
Southland	88.6	10.9	0.5	0.0
Stewart Island	89.6	10.4	0.0	0.0
Taieri	81.6	18.4	0.0	0.0
Waitaki	79.4	17.1	3.4	0.0
Westland	69.9	19.9	9.5	0.7
South Island total	**78.5**	**19.6**	**1.9**	**0.1**
North Island				
Auckland	0.0	77.4	22.6	0.0
Bay of Plenty	9.7	71.7	18.6	0.0
Coromandel	0.0	82.0	18.0	0.0
East Cape	8.0	75.2	16.9	0.0
Hawkes Bay	46.2	49.5	4.3	0.0
Manawatu-Wairarapa	29.6	68.3	2.1	0.0
Mokau	0.0	92.9	7.1	0.0
Northland - eastern	0.0	76.9	23.1	0.0
Northland - northern	0.0	0.0	0.0	0.0
Northland - western	0.0	86.6	13.4	0.0
Palliser-Kidnappers	0.0	96.8	3.2	0.0
Taranaki	0.0	97.9	2.1	0.0
Waikato	18.6	70.7	10.7	0.0
Wanganui-Rangitikei	28.0	65.3	6.8	0.0
Wellington	50.5	49.5	0.0	0.0
North Island total	**18.5**	**72.0**	**9.4**	**0.0**
All NZ Grand Total	**50.5**	**44.0**	**5.4**	**0.0**

Figure 2: **River reaches in New Zealand sharing the REC classes found in the *D. geminata*-affected reaches in the Mararoa and lower Waiau Rivers. The colour coding reflects the frequency of the different stream section classes in the current range of the species (Mararoa and Lower Waiau Rivers): grey, no reaches; yellow, lowest frequency; red, highest frequency.**

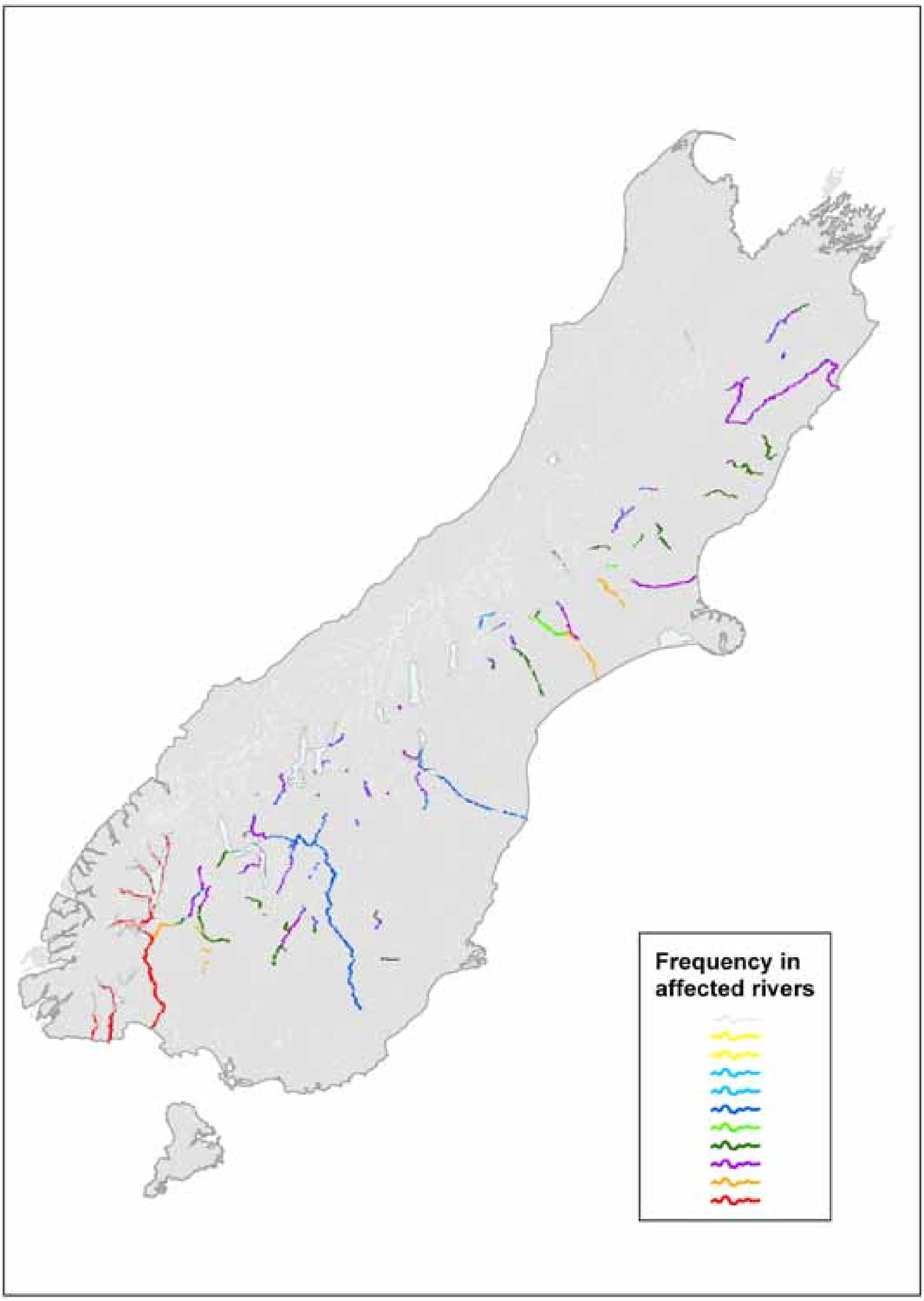

Figure 2 (contd).

Table 6: REC classes represented in the areas of lower Waiau and Mararoa Rivers affected by *D. geminata*.

Reach classification	No. sections	Colour coding in Figure 1
CX/Lk/Pl/IF/HO/LG	160	
CW/H/Al/P/HO/LG	31	
CW/M/HS/T/HO/LG	23	
CW/H/HS/T/HO/LG	16	
CW/H/Al/T/HO/LG	5	
CW/Lk/HS/T/HO/LG	4	
CW/M/HS/T/HO/MG	2	
CX/Lk/Pl/IF/HO/MG	2	
CW/H/Al/P/HO/MG	1	
CX/Lk/Pl/IF/HO/HG	1	
Total	245	

Table 7: Distribution of the REC classes represented in the affected areas of the Mararoa and lower Waiau Rivers among bioregions defined in the Waters of National Importance project. North Island bioregions with 0% reaches are not shown.

	WONI bioregion	Percentage of total stream length with the same REC classes as those in the *D. geminata*-affected rivers	Percentage of high order stream sections with the same REC classes as those in the *D. geminata*-affected rivers
South Island	Banks Peninsula	0	0
	Canterbury	1.07	20.3
	Clutha	1.34	28.6
	Fiordland	0.80	55.0
	Grey-Buller	0	0
	Marlborough	1.70	32.5
	Motueka-Nelson	0	0
	Northwest Nelson-Paparoa	0	0
	Otago Peninsula	0	0
	Southland	1.70	32.7
	Stewart Island	0	0
	Taieri	0.25	4.7
	Waitaki	0.65	14.4
	Westland	0	0
North Island	Manawatu-Wairarapa	0.08	1.32

distance of river reach in each bioregion. River reaches with REC classes matching those of the affected rivers make up a very small proportion (<2%) of the total length of river reach in all of the WONI bioregions. This is mainly because the affected reaches are all high order, thus restricting the selection to the main stems of rivers. In other words, based on its present distribution in New Zealand, *D. geminata* only occurs in high-order rivers (i.e., the main stems of rivers). Since the main stems of rivers comprise only a small proportion of the total length of streams in a catchment, the low percentages in each bioregion were expected. For comparison, the table also shows the percentage of *high order* streams in each bioregion occupied by the REC classes of the affected rivers. The high percentage for Fiordland (55%) reflects the fact that most streams in the region are low order.

5. Conclusions

The risk stratification (Figure 1, Tables 4, 5) indicates that rivers in many parts of South Island are in the highest risk category of susceptibility to *D. geminata* establishment and growth, based on our assessment of what constitutes a favourable environment for this species. The currently affected rivers are in the highest risk band, as well as other streams in Southland and Otago, the eastern foothills of the Southern Alps, and the Kaikoura Ranges. Several rivers in the northwest of the South Island also fall into the highest risk category, as do the lower reaches of some West Coast streams. Fiordland is mostly in the moderately "at risk" range, presumably as a result of high rainfall and steep gradients. Many West Coast streams fall into the lower risk groups, probably as a result of high rainfall, but also due to shading, high occurrence of peat, and high gradients.

The result for Stewart Island suggests a relatively high overall risk, which we believe may not be accurate. Because Stewart Island was never included in the LRI, from which the peat variable was derived, this information is not represented for that area. The island has extensive peat cover and many brown-water streams, implying that the risk is very likely lower than suggested by the analysis.

The overall much lower risk computed for North Island is consistent with our understanding that *D. geminata* is almost invariably found in cooler, mountainous regions. Literature information relating to temperature preferences is limited, but the evidence suggests that the species may have an upper tolerance limit, possibly around 21 to 23ºC. Thus in the North Island, highest risk areas include the Central Volcanic Plateau, and some rivers draining higher altitude areas such as the Tararua, Ruahines and Raukumara Ranges. Some areas of the North Island may be at relatively low risk because of the high incidence of very soft mudstone and siltstone in their catchments.

Tables of the distribution of stream reaches in the WONI bioregions showed that the bioregions likely to be most affected, according to the criteria used for ideal habitat for *D. geminata*, are Southland, Clutha, Waitaki and Marlborough, all in the South Island. In the North Island, Wanganui-Rangitikei and Hawkes Bay contained the highest percentages of stream length with the more suitable environments. Over the whole country, more than 12% of the river reach lengths fell into the 25% of environments (based on the 100 groups) closest to the "ideal" *D. geminata* environment.

In almost all WONI bioregions, percentages of stream length in the highest-risk group were considerably higher when calculated using high order REC stream sections only (Table 5), instead of using the entire REC network. This suggests than the main stems or larger tributaries of rivers are more at risk from *D. geminata* establishment than are lower order, smaller streams, according to our analysis.

This analysis has been based on quite sparse and often qualitative published information about the environmental preferences and distribution of *D. geminata*. In addition, the environmental information describing New Zealand rivers is based on averaged data at a stream reach scale, although it is detailed on a national scale. We also acknowledge that local conditions in some areas may mean that factors unaccounted for in the REC data may make river sections more, or less, likely to be suitable for *D. geminata* than indicated by the analysis. Therefore, at the scale of a river section or less, the maps should not be interpreted absolutely literally. However, on a broad scale, we believe that the stratification of risk corresponds well with our understanding of the environmental requirements of *D. geminata* reported from overseas, and its distribution on a global scale.

Since completion of this analysis information has come to hand of *D. geminata* proliferating in warmers areas of the USA, e.g., locations in Arkansas. This suggests that *D. geminata* may have a broader temperature tolerance than assumed, and the maps produced by the present analysis should therefore be interpreted as conservative, particularly for warmer regions of New Zealand. More information is required on the environmental conditions associated with these growths before any definite conclusions can be drawn.

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Appendix 1

Details of the clustering and similarity analyses used to define the stratification of New Zealand's rivers according to suitability for *D. geminata*

The stratification (clustering of individual sections of the river network) was performed in the multivariate analysis package PATN (Belbin 1995). Our choice of a clustering strategy was strongly constrained by the size of the data array requiring analysis, and this prevented the direct use of hierarchical clustering procedures for which processing requirements rise rapidly with increasing dataset size. The clustering was therefore performed in two stages. In the first stage, a non-hierarchical clustering procedure (ALOC – Belbin 1995) was used to sort the segments into 100 groups. This procedure carried out an initial allocation of sections to groups based on their environmental distances from each other. It then performs an iterative testing phase during which each point is removed from its allocated group, the distance between it and each of the groups is recalculated, and it is placed in the group to which it is closest. This procedure is repeated until either a set number of iterations has been performed, or until no further relocations of points to groups can be made.

We used the Gower metric to measure environmental distances between sites (Sneath & Sokal 1973), was used as the measure of environmental distance. The Gower metric is defined as:

$$D = \sum_{i=1}^{n} \left| \frac{x_{ij} - x_{ik}}{range(x_i)} \right|$$

where *D* is the environmental distance between points *j* and *k*, which are described by a set of variables $x_{1\sim n}$. This distance measure is a range standardised Manhattan type distance measure that effectively gives each variable equal weighting.

At the next stage we computed the mean value of the defining variables for each of the 100 groups. We then used these mean values to compute a distance matrix for all pair-wise distances between groups. We again used the Gower metric to compute these inter-group distances. After we identified the most suitable group for *D. geminata*, we used the row and column in the distance matrix to define the distance of all other groups to the most suitable group. This table of distances could be attached to the river network (using the membership of each network section to the 100 clusters as the joining index). The stratification could then be mapped by colouring each network section according to a graduated colour that was determined by the value of the distance from the most suitable group.

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Appendix 2

Mean values of the eight selected environmental variables in the 100 groups of river sections produced by the cluster analysis.

Values assigned to describe the "ideal" environment for *Didymosphenia geminata* are shown, and the 100 groups are listed in increasing order of their statistical distance from the ideal. Note that AvTWarm was quadruple-weighted and usLake double-weighted

Group	Distance	AvTWarm	usLake	usHard	usRainDays25	segSlope	segShade	usPeat	usGlacial
"ideal"		**10**	**0.6**	**4**	**0.6**	**0.01**	**0.04**	**0**	**0**
76	0.133	9.8	0.006	4.01	0.74	0.081	0.13	0.0007	0.0003
96	0.144	13.7	0.838	4.78	0.87	0.000	0.03	0	0
38	0.146	11.2	0.033	3.95	1.46	0.009	0.03	0	0.0166
78	0.146	11.7	0.012	3.77	0.57	0.019	0.11	0.0021	0.0006
80	0.168	13.1	0.012	3.42	0.57	0.005	0.05	0.0018	0.0026
74	0.173	14.3	0.925	3.08	1.11	0.000	0.01	0	0
65	0.176	9.5	0.004	3.94	2.56	0.039	0.05	0	0.0862
7	0.177	15.9	0.873	3.92	0.96	0.000	0.01	0	0
94	0.179	13.9	0.749	3.15	1.22	0.002	0.32	0	0
95	0.184	10.7	0.002	3.95	0.66	0.133	0.42	0.001	0
73	0.185	11.7	0.069	3.74	1.23	0.003	0.00	0	0.357
34	0.191	14.3	0.931	1.88	1.04	0.000	0.03	0	0
58	0.196	11.1	0.005	3.84	3.11	0.015	0.08	0.0002	0.0368
16	0.201	13.0	0.003	3.46	0.54	0.025	0.33	0.0017	0
83	0.202	15.7	0.878	1.98	0.49	0.000	0.01	0	0
19	0.207	7.7	0.003	4.04	0.88	0.251	0.10	0	0.001
86	0.212	10.0	0.003	4.08	1.82	0.194	0.41	0	0.0042
48	0.213	13.6	0.009	3.58	1.91	0.016	0.11	0.0004	0.0007
69	0.214	14.9	0.040	2.96	0.96	0.005	0.04	0.0009	0
91	0.215	8.1	0.002	3.98	1.78	0.196	0.12	0	0.026
17	0.215	12.3	0.001	3.85	0.56	0.087	0.54	0.001	0
98	0.215	14.1	0.005	2.49	0.51	0.008	0.16	0.0047	0
23	0.217	17.2	0.944	3.37	0.96	0.000	0.00	0.0002	0
29	0.218	8.8	0.003	4.30	0.87	0.223	0.39	0.0001	0.0005
44	0.218	15.3	0.799	4.12	3.30	0.000	0.04	0	0
68	0.227	9.4	0.001	4.01	0.66	0.242	0.65	0.0003	0.0004
35	0.231	16.4	0.751	1.73	0.38	-0.003	0.25	0	0
77	0.235	11.0	0.000	4.02	0.59	0.203	0.73	0.0006	0
81	0.236	15.2	0.963	0.02	0.79	0.000	0.01	0	0
13	0.237	16.1	0.010	3.28	0.86	0.006	0.10	0.0005	0
45	0.239	16.8	0.930	2.04	1.24	0.000	0.01	0	0
40	0.244	12.6	0.002	3.92	1.99	0.073	0.48	0.0004	0.0002

Group	Distance	AvTWarm	usLake	usHard	usRainDays25	segSlope	segShade	usPeat	usGlacial
“ideal”		**10**	**0.6**	**4**	**0.6**	**0.01**	**0.04**	**0**	**0**
54	0.246	9.4	0.001	4.10	3.10	0.183	0.31	0	0.0396
100	0.248	15.1	0.002	3.67	0.89	0.036	0.39	0.0004	0
92	0.252	9.9	0.002	4.83	1.05	0.247	0.73	0	0.0001
33	0.254	14.1	0.001	2.35	0.57	0.026	0.48	0.0017	0
75	0.256	12.3	0.000	4.02	0.53	0.167	0.77	0.0006	0
18	0.259	13.3	0.000	3.69	0.38	0.089	0.70	0.0008	0
87	0.263	10.7	0.001	4.05	3.15	0.155	0.53	0	0.0191
71	0.265	7.8	0.000	4.02	2.98	0.174	0.04	0	0.3032
22	0.267	17.0	0.012	2.70	1.24	0.004	0.05	0.0018	0
42	0.267	13.8	0.022	3.30	3.20	0.018	0.22	0.0054	0.0004
79	0.270	12.6	0.000	2.32	0.73	0.089	0.72	0.0004	0
14	0.273	17.1	0.970	0.34	1.03	0.000	0.00	0.0009	0
89	0.273	10.3	0.000	4.13	1.88	0.272	0.75	0	0.0014
30	0.273	15.8	0.002	2.35	1.72	0.013	0.14	0.0033	0
12	0.274	18.3	0.644	0.96	1.32	0.002	0.20	0	0
39	0.279	14.2	0.000	3.89	0.49	0.111	0.75	0.0004	0
70	0.279	16.4	0.592	1.07	0.42	0.000	0.71	0.0294	0
56	0.279	15.5	0.859	1.06	3.30	0.000	0.07	0	0
93	0.280	16.3	0.002	2.90	0.86	0.020	0.40	0.0004	0
55	0.280	6.5	0.001	4.03	2.57	0.305	0.04	0	0.0274
20	0.284	17.3	0.002	3.51	1.29	0.018	0.27	0.001	0
53	0.284	8.1	0.001	4.14	3.17	0.328	0.15	0	0.0229
15	0.286	15.4	0.000	3.75	0.60	0.067	0.71	0	0
85	0.288	12.3	0.000	2.96	0.53	0.049	0.73	0.4855	0
31	0.292	14.2	0.000	2.14	0.38	0.034	0.72	0.0012	0
5	0.292	18.4	0.005	2.91	1.08	0.004	0.12	0.0117	0
88	0.294	8.4	0.001	4.18	1.80	0.385	0.52	0	0.0108
99	0.297	13.9	0.005	1.94	0.44	0.003	0.49	0.4007	0
67	0.297	11.9	0.000	4.37	1.91	0.223	0.77	0	0
25	0.301	16.6	0.000	3.85	0.63	0.047	0.71	0.0002	0
28	0.303	13.4	0.000	3.96	1.43	0.201	0.78	0.0002	0
57	0.304	8.7	0.001	4.22	3.10	0.299	0.50	0	0.0202
62	0.306	8.1	0.000	4.04	3.03	0.245	0.28	0	0.3548
36	0.308	16.1	0.961	0.36	0.40	-0.009	0.63	0.0059	0
82	0.311	16.7	0.001	3.62	1.38	0.062	0.54	0.0004	0
9	0.312	17.6	0.003	1.75	1.02	0.009	0.27	0.0069	0
43	0.319	9.5	0.000	4.19	3.16	0.330	0.72	0	0.0116
52	0.319	0.0	0.044	4.32	0.00	0.000	0.23	0	0
61	0.320	16.3	0.000	2.94	0.96	0.055	0.69	0.0004	0
51	0.322	14.7	0.000	3.95	1.59	0.166	0.76	0.0001	0

Group	Distance	AvTWarm	usLake	usHard	usRainDays25	segSlope	segShade	usPeat	usGlacial
"ideal"		**10**	**0.6**	**4**	**0.6**	**0.01**	**0.04**	**0**	**0**
11	0.323	15.9	0.001	2.15	0.44	0.029	0.74	0.0004	0
64	0.323	8.2	0.000	4.13	3.11	0.191	0.60	0	0.2801
27	0.324	16.0	0.001	2.09	1.65	0.037	0.51	0.002	0
46	0.325	15.3	0.010	1.70	3.21	0.007	0.26	0.005	0
41	0.326	14.6	0.000	2.32	1.28	0.100	0.78	0.0003	0
8	0.327	18.5	0.001	2.99	1.09	0.012	0.44	0.005	0
26	0.329	16.0	0.000	3.81	1.26	0.113	0.78	0.0001	0
60	0.329	7.1	0.000	4.02	3.02	0.247	0.03	0	0.6746
3	0.332	18.1	0.000	3.70	1.07	0.040	0.62	0.002	0
90	0.334	11.3	0.000	4.19	3.19	0.308	0.77	0	0.002
63	0.337	13.1	0.000	3.78	3.17	0.183	0.75	0.0008	0.0003
66	0.340	6.0	0.000	4.09	2.70	0.329	0.02	0	0.4516
32	0.344	17.0	0.001	1.19	0.67	0.014	0.65	0.0051	0
10	0.346	17.5	0.000	2.29	1.21	0.040	0.59	0.0004	0
1	0.351	17.5	0.000	3.76	1.32	0.082	0.78	0.0002	0
4	0.361	18.7	0.000	3.15	1.07	0.032	0.73	0.0032	0
6	0.363	18.3	0.016	1.39	0.94	0.001	0.16	0.4949	0
37	0.367	16.5	0.000	2.18	1.45	0.089	0.78	0.0002	0
47	0.368	14.9	0.001	2.12	3.19	0.043	0.74	0.0022	0
84	0.371	13.8	0.000	1.17	0.40	0.002	0.64	0.8883	0
2	0.376	18.6	0.000	1.36	1.02	0.011	0.65	0.0056	0
59	0.393	5.6	0.000	4.03	3.02	0.310	0.00	0	0.8903
24	0.400	18.7	0.001	1.60	0.97	0.003	0.57	0.3752	0
97	0.401	0.0	0.001	2.73	0.00	0.053	0.75	0	0
49	0.404	15.0	0.005	1.63	3.29	0.002	0.56	0.5126	0
72	0.418	3.5	0.000	4.03	3.18	0.234	0.00	0	0.8817
50	0.442	15.8	0.004	1.11	2.58	0.002	0.57	0.8612	0
21	0.458	18.5	0.000	1.07	0.93	0.001	0.60	0.9023	0