EFFECTS OF CLIMATE AND LAND USE CHANGE ON INVASIVE SPECIES: A CASE STUDY OF *TRADESCANTIA FLUMINENSIS* (VELL.) IN NEW ZEALAND

A thesis
submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy
at the International Global Change Institute (IGCI)
The University of Waikato

by

Liza Preethy Storey

University of Waikato
2009

Abstract

Climate change, land use change and invasive species are transforming global biodiversity at multiple scales. Projections are for threats to biodiversity from these global changes to continue into the future, with varied and discernible distribution changes for many species. Concomitantly, these global changes will interact with each other to further exacerbate the problem, as exemplified in this study. In New Zealand, climate change is expected to affect landscapes, fragmented and disturbed by land use change, further increasing the potential invasibility of these landscapes for a suite of existing and emerging invasive species.

This thesis is concerned with the combined effects of climate and land use changes on the spatial distribution of the sub-tropical invasive plant, *Tradescantia fluminensis* (Vell.). The contribution of this thesis is to undertake an integrated assessment of the distribution change for this species in New Zealand. On the basis that climatic variables affect species distribution at larger scales, while land use, habitat, disturbance and dispersal mechanisms affect distribution at smaller scales, two separate analyses were undertaken. At the national scale BioCLIM and the Ecological Niche Factor Analysis (ENFA) were implemented using the variables: minimum temperature (July-August), MTminJ-A, and annual water deficit (November-February). At the landscape scale, only ENFA was implemented, using the variables: MTminJ-A, ECOSAT riparian classes (habitat) and proximity to roads, urban areas and streams (disturbance and dispersal sources). Three scenarios of climate change (CCSR B1-Low, CSIRO9 A1B-Mid and HadCM A1FI-High) and two scenarios of land use change (SmartGrowth and Buildout) were developed to the year 2050, using the CLIMPACTS Open Framework Modelling System and Geographic Information Systems, GIS, techniques respectively. The baseline species distribution model was extrapolated in ENFA, using the 2050 scenarios. Changes to potential threat from this species to protected areas at the landscape level were assessed spatially at the landscape level. This approach and its results are novel for this species.

At the national scale the results for the modelling show that climate change will increase the potential habitat suitability of *Tradescantia* under all combined scenarios of CCSR, CSIRO9 and HadCM for mean minimum temperature (July-August), MTminJ-A and Annual Water Deficit, AWD. At the case study landscape, in the Western Bay of Plenty and Tauranga also the modelling results showed that climate change *and* land use changes will increase the suitability for *Tradescantia* by 2050.

The 'core' or highest suitability areas increase under all future scenarios. At the national level core suitability increased by about 13% for the CCSR:B1-Low and CSIRO9:A1B-Mid and 22% for HadCM:A1FI-High combined scenario on the North Island. On the South Island, core areas increased by a much lower margin – 1.4%, 2.3% and 2.9% for CCSR:B1-Low, CSIRO9:A1B-Mid and HadCM:A1FI-High combined scenarios respectively. At the landscape level core areas increased by 5%, 8% and 21% for the CCSR:B1-Low+SmartGrowth, Darlam:A1b-Mid+SmartGrwoth and HadCM:A1FI-High+Build-out combined scenarios, respectively. This is true also for the Protected areas within the case study landscape, and indicate that the increasing if Tradescantia is able to track both climate and land use change through its dispersal and migration within the landscape 9 primarily in the inland and upland direction), then is will pose a greater risk to native habitats than at present.

Integrated assessments and the outputs they produce are essential to exploring anticipated changes (through scenario-building) and in understanding the change spatial context and magnitude of projected changes from the combined effects of climate and land use changes into the future and need to be integrated into biodiversity-biosecurity management at multiple scales.

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1 Chapter 1: Topic overview and thesis organisation

1.1 Introduction

This thesis is concerned with the combined effects of climate and land-use changes on invasive pest plants. The aim of the thesis is to undertake an integrated assessment based on spatially-explicit species distribution modelling of climate and land-use changes in relation to one case study species, *Tradescantia fluminensis* (Vell.), at the national and landscape-levels in New Zealand. The case study landscape is the Western Bay of Plenty and Tauranga. Scenarios of change, to the potential species distribution of *Tradescantia*, are developed given various projections of change in both climate and land-use, and the realised distribution of *Tradescantia* in New Zealand. The integrated assessment and its methodological approach are intended to be useful for decision-making within New Zealand's existing biosecurity system and can be applied to other plant species as well. This is the first spatially-explicit integrated assessment to be undertaken for *Tradescantia fluminensis*, and the first time that spatially explicit scenarios of climate change and land-use change (linked to regional biodiversity and urban development targets) are combined, at the landscape-level, for an integrated assessment of effects in New Zealand.

The remainder of this Chapter provides a broad overview of the research topic and thesis organisation. It provides the rationale for the present study and its significance, as well as a statement of the research objectives and tasks undertaken. Section 1.2 gives an overview of the research topic relating to climate change, land-use change and invasive plants. Section 1.3 covers the scale of the invasive plant problem in New Zealand. Section 1.4 defines the case study focus, while Section 1.5 details the research development of this thesis, including the research question, aim and objectives, methodological approach taken, research contribution and the thesis outline.

1.2 Climate change, land use change and invasive plants: an overview

Climate change, land-use change and the spread of invasive species are three major global change processes that threaten the condition, and management of biodiversity at multiple scales (Thomas et al., 2004; Walther et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003; Sala et al., 2000; and Dukes and Mooney, 1999). Sala et al., (2000) have ranked the relative importance of the main global change drivers to develop global biodiversity scenarios for the year 2100, and state that for terrestrial systems, land-use change will probably have the largest effect, followed by climate change, nitrogen deposition, biotic exchange (including invasive species spread) and elevated atmospheric carbon dioxide concentrations. Invasive species are considered significant global change agents, while at the same time are also responding themselves to other global change drivers that positively facilitate their spread in vulnerable landscapes. Figure 1.1 gives a conceptual model, showing the various elements which favour invasive species and increase the supply of their plant propagules. Feedback on global change will be positive or negative depending on the invading species and on the element of global change (Dukes and Mooney, 1999).

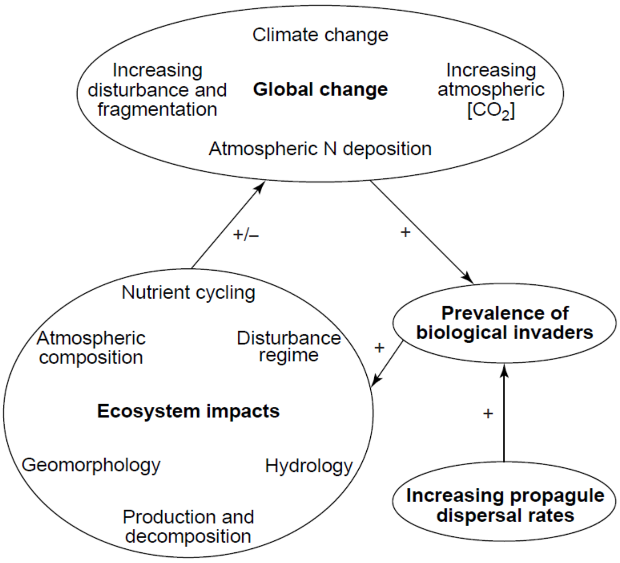

Figure 1.1 Interlinkages of global change processes in invasive species spread. (Source: Dukes and Mooney, 1999, pg 137, used with permission).

Land-use changes, particularly urban expansion and habitat loss and fragmentation through vegetation clearance and agricultural or forestry activities, continue to open new areas to exotic planting and altered disturbance regimes which are conducive to the establishment and spread of invasive plants (With, 2002 and 2004; Dirnböck et al., 2003; Mooney and Hobbs, 2000; Lonsdale, 1999; UNEP, 2002 and Gill and Williams, 1996). Climate change is projected to alter temperature and precipitation regimes, extending the climatic suitability for some species, e.g. tropical and sub-tropical invasives plants (Thuiller et al., 2005; Pearson and Dawson, 2003; Kriticos et al., 2003a and b). Nitrogen enrichment from land use-related disturbances has doubled the rate of nitrogen input into the terrestrial nitrogen cycle (Vitousek et al., 1997), which is conducive to the growth of opportunistic invasive plants through localised nitrogen deposition. International and domestic trade in exotic species (for ornamental, horticultural, and agricultural purposes) and accidental introductions continue to cause shifts in the biogeographic boundaries of species around the world (Williams and West, 2000). In New Zealand, as elsewhere, garden planting and subsequent green-waste dumping by people has facilitated the transport and successful establishment of numerous invasive plants in fragmented natural areas and riparian habitats in lowland areas. The landscape-level *invasibility*, or vulnerability of habitats within a landscape to invasion, is known to be interlinked with climatic, land use, disturbance and landscape-level factors and will be further explored in this thesis.

Invasive plants affect biodiversity conservation by characteristic degradation and modification of habitats, through for instance: competition with native plants for light, nutrients, moisture, and space; replacement of indigenous plant communities; prevention of natural regeneration; altering disturbance, and water regimes; changing the nutrient status of the soil humus; removing or introducing new food sources; or altering sedimentation processes (Stohlgren et al., 2001; Williams and West, 2000). In addition to this, in New Zealand, many invasive weeds do not have natural competitors (within genus) (Duncan and Williams, 2002). As a result, they appear to have a competitive advantage once naturalised in suitable habitats in the wild.

The significance of these impacts is strikingly obvious in urban and peri-urban forest fragments, bush remnants, gully corridors and riparian networks. For instance, in Auckland, New Zealand, the world's 'weediest city', Gould (2000) states that almost all of the bush remnants have native canopy trees being replaced by invasive tree privet, exotic ground cover such as wandering creeper (*Tradescantia fluminensis*) and wild ginger (*Hedychium gardnerianum* and *H. flavescens*). Nationally and regionally significant areas of biodiversity are also at risk within city boundaries (Gould, 2000). Increasingly, the conservation of region-specific native biodiversity is undermined, as impacts of introduced invasive plants modify ecosystems (Hobbs, 2001) competing for resources, replacing native species and impeding their regeneration (Merriam and Feil, 2002). The costs of controlling these invasive species is high, with New Zealand spending an estimated $840 million per year in environmental and control costs for all pests including plant and animal species (Pimentel, 2002).

The problems caused by invasive plants that affect indigenous vegetation and native ecosystems, known as *environmental weeds* in New Zealand, cannot be stated in simple economic or agronomic terms (e.g. the loss of produce yield caused). This is because the threat is broader, and concerns issues of ecosystem stability, functional complexity and biodiversity (Adair & Groves, 1998) and non-monetary valuations of ecosystem values and services lost. As a result, environmental weeds represent a particular challenge for natural resource managers (Williams and West, 2000). The sensitivity of these environmental weeds to climate and land-use changes will influence their potential future impacts on indigenous biodiversity in New Zealand and further necessitates adequate capabilities to assess the effects and be able to make anticipatory changes where needed and feasible. The following section addresses observed climate changes and the links to invasive species.

1.2.1 Climate change and invasive pest plants

1.2.1.1Observed climate changes

Climate change has been widely attributed to the observed changes in concentrations of atmospheric greenhouse gases and aerosols, solar radiation and land surface properties which alter the energy balance of the earth’s climate system. These changes are expressed in terms of ‘radiative forcing’, which is used to compare how a range of human and natural factors drive warming or cooling influences on the climate (IPCC, 2007a). Direct observations of recent climate warming show that there is a clear warming trend in the climate system evident from increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. The updated 100-year linear trend (1906 to 2005) of 0.74°C [0.56°C to 0.92°C], given in the recent Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), is therefore larger than the corresponding trend for 1901 to 2000 given in the Third Assessment Report (TAR) of the IPCC, of 0.6°C [0.4°C to 0.8°C]. The linear warming trend over the last 50 years (0.13°C [0.10°C to 0.16°C] per decade) is nearly twice that for the last 100 years. The total temperature increase from 1850–1899 to 2001–2005 is 0.76°C [0.57°C to 0.95°C] (IPCC, 2007a). For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES[1] emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade is expected. Figure 1.2 illustrates the distinct rise in major greenhouse gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

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[1] SRES – Special Report on Emissions Scenarios (Nakićenović, et al., 2000) used by the IPCC. These SRES scenarios will be further discussed in Chapter 5 which looks specifically at generating climate change scenarios for this thesis.

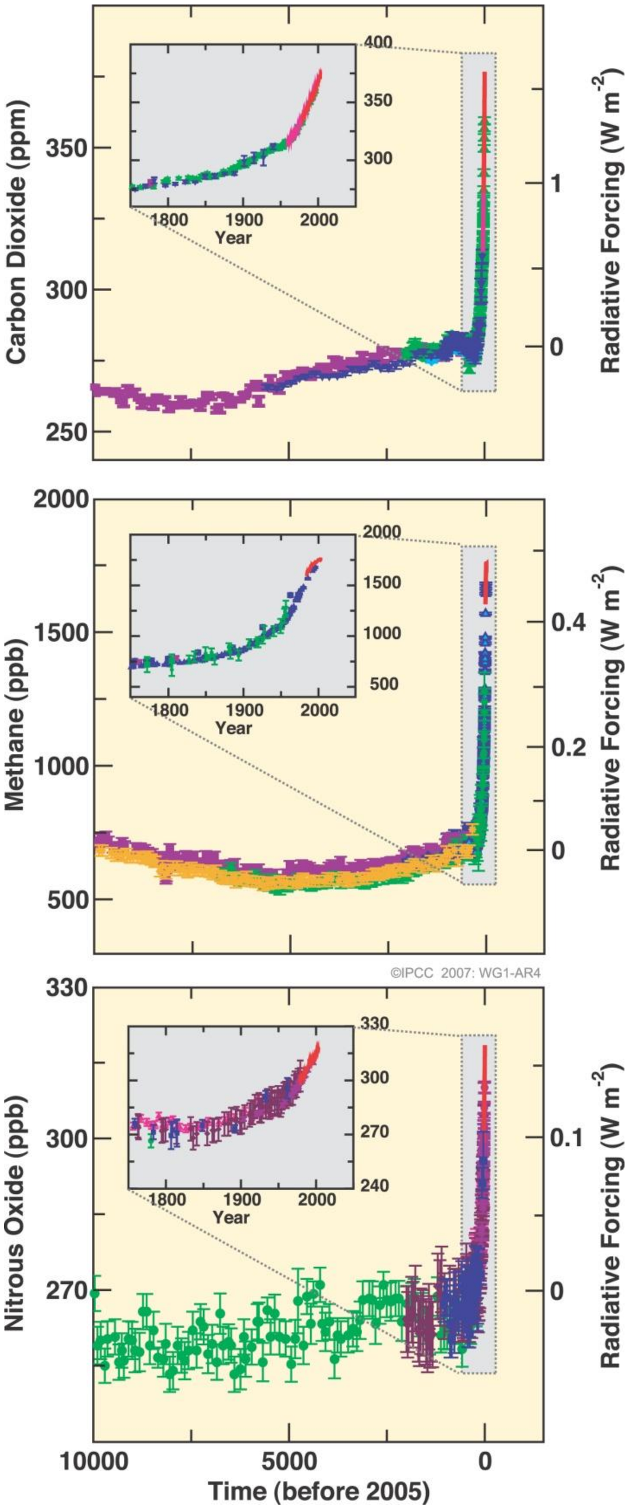

Figure 1.2 Changes in greenhouse gases (GHGs) as a combination of ice core and modern data. Sharp rises in the atmospheric concentration of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) in recent times (represented as year before 2005) are evident relative to historic trends (Source: IPCC, 2007c, pg. 3, used with permission).

It is still difficult to make full predictions of the changes which will occur to global, regional and local climatic regimes. However, there is now increasing potential to use integrated assessment models, which incorporate multiple disciplines, to understand climate change impacts and vulnerability and to create possible *scenarios* of the future changes to primary climatic variables such as temperature and precipitation (or other derived variables of precipitation, such as water deficit). These scenarios portray the environmental changes to which different species, ecosystems or sectors are sensitive (Clark, 1991; Kenny et al, 1995; Dirnböck et al., 2003). This scenario-based approach is central to this thesis.

1.2.1.2Effects of climate change on invasive pest plants

Climate change, particularly regional temperature increases, has already been affecting physical and biological systems globally (very high confidence, i.e. a 9 out of 10 chance according to IPCC likelihood terminology) (IPCC, 2007b). This has been referred to as the ‘fingerprint’ of climate change by Parmesan and Yohe (2003). The resultant impacts of invasive species on native ecosystems in novel environments will be influenced by the changes in physiology, spatial distribution, prevalence and abundance of the species under future scenarios of climate change (Hughes, 2000) and equally importantly, land-use change. Kriticos et al., (2001) state that by knowing the change and the direction of change and the relative sensitivity of the potential distribution to climate change scenarios (of the climatic variables that the species is sensitive to physiologically), it is possible to assess the likely changes to the invasion risk or impacts posed by particular species.

Species’ responses to climate change often vary, because although climate may be the major factor influencing distribution at the broad scale, at more local scales, proximate localized factors relating to land cover and land use, e.g. habitat availability, propagule pressure (Higgins and Richardson, 1999) local extinctions and colonization dynamics of metapopulations (Holt & Keitt, 2000), adaptability (Thomas et al., 2001), and species interactions and dispersal (Davis et al., 1998) may be more important (see Figure 1.3 for relative dominant effects of variables at various scales). The climatically suitable space available, best represents a maximum potential future distribution that is unlikely to be fully spatially realized due to more local factors and, more importantly, the dispersal limitation that must be overcome in order to fill all or parts of the new potential range (Berry et al., 2002). As a result it is important that more detailed, local landscape-level assessments, which incorporate land use and land cover, are included to take account of more mechanistic and habitat-orientated variables. This will be discussed in Section 1.2.2.

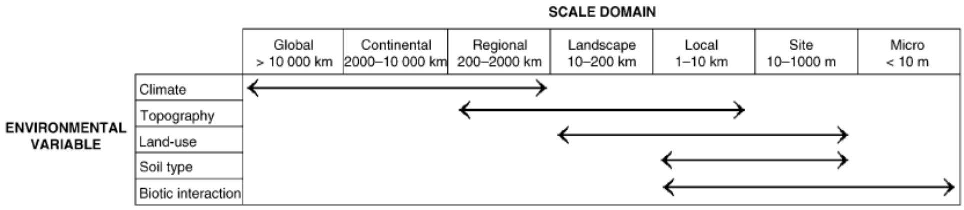

Figure 1.3 Scale domains of major environmental variables. It is assumed that the large spatial extents are associated with coarser data resolutions and small extents with fine data resolutions (Source: Pearson and Dawson, 2003, pg. 368, used with permission).

The habitat suitability for a species is linked with climate, land use/land cover, landscape pattern and process, and dispersal pathways – aided or natural. These factors play an important role in facilitating the establishment and spread of invasive species and show scale-dependencies in how they influence invasive species distribution. Climatic controls are typically associated with gross suitability at larger scales (for instance global to national), while land use and landscape-level factors are associated with more regional to local-level effects on distribution (for instance at the landscape-level) (Berry et al., 2002). Further discussion of the geographic range of a species and how that relates to the integrated assessment and modelling efforts will be covered in Chapter 3.

The geographic expansion of a species' range and changes in the timing of seasonal events related to its reproduction and growth, have generally been attributed to "phenotypic plasticity", which is the ability of individuals to modify their behavior, morphology, or physiology in response to altered environmental conditions (Bradshaw and Holzapfel, 2006; Hughes, 2000 and Walther et al., 2002). Herbaceous plants, such as many invasive plant species, adapt relatively quickly to changing conditions and may provide evidence of climate change through their wide amplitude of acclimation and their overall vivid differentiation of ecotypes (Larcher, 2003). This amplitude of acclimation is also referred to as phenotypic plasticity, and is commonly exhibited in invasive plants (Burns, 2006). Some vigorous invasive pest plants demonstrate shorter-term plastic responses for example the positive biomass accumulation response of *Tradescantia fluminensis* to elevated levels of soil nitrate, (Burns, 2006) or longer-term genetic responses (IPCC, 2001) that further enhance their acclimation and suitability in non-native habitats, and increase the potential risk faced by invaded habitats in novel environments.

Furthermore, stress physiology plays an important role in elucidating the species responses to extreme climatic variations over short to long time scales, for instance, plant responses to extreme temperature-induced frosts or drought events. Various studies suggest that while climate change affects broad assemblages of species/communities as a whole, it is likely to eventuate in 'individualistic' responses of species; given that individual species migration rates will vary (Berry et al., 2002). Studies such as Davis et al. (1998) however, are not in agreement with this view that species distributions are influence by species responses to climate (therefore using climate mapping techniques) alone, instead arguing that inter-specific competition and interactions, as well as species dispersal capabilities will influence future species distributions, and as a result climate mapping alone will not reflect future responses of individual species to environmental change. Species with better dispersal mechanisms, especially for long-distance dispersal

(Higgins and Richardson, 1999), will have an advantage (this holds true for many invasive species, Dukes and Mooney, 1999).

With respect to assessing species distribution of invasive species in response to climate change, the few predictions that have been made have primarily concentrated on the likely changes in the distribution ranges of *established* invasive species (Kriticos, 2003a and b). This effect is likely to be substantial, particularly as global warming will make much of what is currently the northern (and southern) temperate zone invasible by more tropical species, of which there are a higher diversity when compared to temperate species. However, some aliens of temperate origin will tend to show overall reductions in the ranges in which they are invasive. This is likely to outweigh the previous phenomenon for reasons of the relative size of temperate and tropical biotas. It is likely, nevertheless, that alien species will more easily out-compete native taxa (Macdonald, 1994).
Due to these changes in climate, the predicted ranges of species under current climatic conditions could increase, decrease or simply shift under future climatic conditions (Kriticos and Randall, 2001; Berry et al., 2002; Pearson et al., 2002; Pearson and Dawson, 2003; Malcom et al., 2002). In order to predict the potential distribution of a species, it is usual to initially analyse its current (baseline) distribution and infer the climatic or other requirements of the species. This prediction can be done using various forms of spatial correlation, such as statistical regression, machine learning techniques, and ad-hoc manual parameter-adjustment (Kriticos and Randall, 2001). A discussion of methods will be undertaken in Chapter 3.

1.2.2 Land-use change and invasive pest plants

Invasions interact synergistically with other components of global change, notably land-use change. Land use denotes the human employment of the land, while land cover denotes the physical and biotic character of the land surface. As a result, land use/land cover change relates to the alteration of the land surface and its biotic cover (Meyer and Turner, 1992). Land cover change takes on two forms: conversion of land cover from one category to another and modification of condition within a category. Changes in areas of vegetation cover (trees for example) are of two kinds: clearance and conversion to another land cover (whether to urban, pasture or horticulture for instance), and change of condition (vegetation 'thinning' without outright conversion, for example) (Adapted from Meyer and Turner, 1992).

Land-use change, like other global changes, is driven proximately by the population growth, industrial and agricultural expansion and economic development, technology changes, peoples' responses to economic opportunities, environmental change (Lambin et al., 2001; Rudel et al., 2005; Houghton, 1994) and per capita resource use (Vitousek et al., 1997).

1.2.2.1Disturbance and invasion

Biological invasions interact with land-use change in several ways. The most obvious of these is through human alteration of disturbance regimes. The association between disturbance and invasion is noted by studies such as Hierro et al., 2006, Marvier et al., 2004, Hobbs and Huenneke, 1996, Mack and D'Antonio, 1998, and humans are now the dominant agents of disturbance on the planet, via multiple land use activities including: agriculture, horticulture, forestry, construction, earthworks, and infrastructure development (roads, channels and others). Moreover, we have not merely increased the frequency and/or intensity of disturbance; in many cases we have created types of disturbances that are unlike anything in the evolutionary history of many species. These alterations have promoted invasion, often by species that are associated with similar disturbances within their original range (Hobbs and Huenneke, 1992).

Land transformation in multiple-use landscapes, encourages biotic change first by causing system changes that provide the opportunity for biological invasion, and second by bringing new species from different bio-geographic regions in contact with altered systems (Hobbs, 2000). Importantly, the disturbance regime, including the type, frequency, duration, and magnitude of disturbance, is recognized as the most important overall factor allowing invasions by exotic species (e.g. Elton 1958; Fox & Fox 1986; Rejmanek 1989). This disturbance is related to the amount of propagule pressure that will be exerted by a species within a landscape. Environmental and habitat characteristics such as temperature, moisture, wind, light, soil type, and plant community type also play a role in invasions (Lindsay 1953; Swincer 1986). Therefore, reflecting the importance of disturbance is important in any species distribution mapping exercises both under current and future conditions.

1.2.2.2Landscape-level invasion patterns

Despite the widespread interest in exotic species invasions, studies incorporating spatially-explicit analyses at a landscape scale are very few (Dark, 2004; With, 2002; Higgins et al., 2000) and those integrating climate change and land use change at the landscape-level even more rare. Landscape-level studies incorporate elements of landscape structure and composition linked to spatial processes that result in various observed species distribution patterns. In this context landscapes are a composition of *patches*, *corridors* and the *surrounding matrix*, each acting as primary habitat, dispersal and movement corridors, barriers to movement or flow pathways for resources, energy and matter needed for a species to establish, grow and disperse and has proven useful for understanding many ecological processes, serving as a basis for making land management decisions (e.g. Forman and Godron 1986; Turner 1987). Temporal and spatial patterns of landscape patches, in particular, have been shown to influence ecological processes (Turner 1989, and 1990). While characteristics of specific areas or ecosystems may influence their invasibility, it may be that landscape-level characteristics of landscape patches, such as age or size, or distance from sources of exotic plant introductions, also influence the distribution and abundance of exotic plants (Song et al., 2005). The landscape is therefore an appropriate scale for studying exotic plant invasions.

For instance old and new residential subdivisions increase the invasion potential at the landscape-level. Gardens are often illegally extended into surrounding forests (patches), and thus act as source populations and sources of disturbance, and dumping of garden refuse also occurs there (Gill and Williams, 1996). Neighbouring land-use is known to be a primary cause by which naturalised plants (including invasive pest plants) can be distributed into patches (Song et al., 2003). A discernible urban-rural gradient in numbers of exotic species in forest patches has been reported, with urban patches having the highest numbers of exotic species followed by peri-urban and then rural patches having the least numbers (Timmins and Williams, 1991; Loewenstein and Loewenstein, 2005; Godfroid and Koedam, 2003; Kowarik 1995). On the other hand, intact and more isolated natural or near-natural ecosystems display a certain ecological resistance against the introduction of alien species (Teo et al., 2003), though there are exceptions (e.g. Higgins et al., 1999) to this trend, which suggest that species richness is not always a robust indicator of ecological resistance.

It can be expected that native plant species of urban/peri-urban forest fragments experience a variety of environmental pressures and respond to a more dynamic environment than forest fragments in less disturbed areas, for instance intact upland forests (Honnay et al., 1999), which in the case of New Zealand, is where the majority of protected areas are located (Norton, 2001). Comparisons between settlements have shown a close relationship between the presence of alien species and the size of urbanised settlements in New Zealand and elsewhere (Timmins and Williams, 1991; Loewenstein and Loewenstein, 2005). This is usually explained by the considerable habitat heterogeneity in urbanised areas, the role of big cities as centres of species immigration (and increased propagule pressure) and the better adaptation of invasive/exotic species to human-made perturbations (Kowarik 1995 and references therein).

As land-use change through urbanisation continues, it is expected that urban pressures will expand into semi-rural areas, and that propagule pressure will increase from ornamental plantings and greenwaste dumping, or natural dispersal of existing populations within the landscape. This continued availability of plant propagules of invasive plants, in combination with disturbance factors that mobilize or facilitate the growth and reproduction of these species, are likely to provide new situations in which invasive species establish and spread into remnant forests and patches in the landscape (Loewenstein and Loewenstein, 2005), forming ‘satellite’ populations.

Most urban habitats are artificial, fragmented, highly disturbed and eutrophic. The net increase in the fertility of soils and urban drainage/stormwater facilitates rapid growth (Lake et al, 2003). The fragmented nature of urban sites often results in large edge-to-area ratios creating extensive opportunity for migration across these borders with more propagule pressure from adjacent residential areas (Swarbrick, 2000; Hobbs, 2001). Forest fragments <9ha are estimated to be edge-influenced (Young and Mitchell, 1994), and microclimatic gradients are estimated to extend 40-50m into forest fragments (Young and Mitchell, 1994; Davies-Colley, Payne and Elswijk, 2000) increasing localized suitability for invasion. Land-use change and fragmentation also create changes in available light, wind speed, humidity, temperature, and soil moisture, which often add to competitive advantages of invasive species over native species (Brothers and Spingarn, 1992). Therefore, a valid connection exists between the study of forest fragmentation and the study of invasive species colonisation (Yates et al., 2004).

Changes in microenvironments (Jones, 1992) caused by the creation of forest edges have led to shifts in species composition at forest margins. Such micro-environmental factors include changes in light availability, soil pH, humidity, air temperature, and soil temperature and moisture between edges and interiors of forest fragments (Honnay et al., 2002). In addition to microclimate variation, anthropogenic soil nutrient gradients can be expected across forest edges, as a result of intensive agriculture in the surrounding landscape matrix (Honnay et al., 2002). Brothers and Spingarn (1992) argue that typical forest-core microclimate conditions are a relatively efficient protection against invasion of aliens, mostly weedy species (Honnay et al., 2002). However, in situations where forest light regimes are altered by the creation of canopy gaps and further penetration of light in the understory and forest floor, this can create new opportunities for invading species establishment. Old temperate forests tend to have a more closed structure and are relatively impermeable. This is due to the well developed shrub and coppice layer and to the sprouting of adventitious limbs in the boundary trees (Honnay et al., 2002).

In order to understand the patterns of spread of an invasive pest plant, scale-dependent analyses of the major dispersal mechanisms and of patch structures of suitable habitats are required (Dietz, 2002). This makes an assessment of landscape-level invasibility very important for New Zealand and one that has so far not been undertaken.

1.3 The scale of the problem in New Zealand

New Zealand has experienced serious negative impacts from invasive species. Thousands of non-native species have been introduced for multiple purposes, being driven in the late 1800s by the newly established Acclimatisation Societies. They promoted the introduction of game animals, birds, fish and plants, and also introduced other species for the control of biological pest species (Druett, 1983).[2] In more recent times, plants continue to be introduced in an even more copious diversity, to supply the exotic garden/nursery trade.

New Zealand’s environmental history reveals that landscapes have undergone extensive fragmentation and modification, primarily for agricultural expansion. Many introduced plants and animals have played a major part in native and managed habitat degradation (Pawson and Brooking, 2002 and Leathwick et al., 2003). Figure 1.4 shows that in the year 2000, there are 24,620 introduced terrestrial plants reported in New Zealand, which has now risen to over 25,000 (Williams and Cameron 2005), compared with 2,350 native plant species. More than 20% of naturalized species are now recognized as weeds by a New Zealand government agency or primary industry (Williams and Timmins, 2002). Figure 1.5 shows the cumulative invasive plants trend, which by 1990 reached a total of 254 environmental weeds. Naturalizing introduced plants are found at a steady rate of more than 12 species/yr (Williams and Timmins, 2002); with new weeds annually accruing on industry and government weed lists. The great majority of these weeds were introduced before New Zealand's recent stringent national biosecurity legislation including the Biosecurity Act 1993 (see: **Error! Hyperlink reference not valid.Error! Hyperlink reference not valid.**).

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[2] Introduced mammals such as the *Trichosurus vulpecula* (Australian bushtail possum), and ruminants, in particular *Cervus* spp. (deer) have rendered significant changes to native forest composition through their selective feeding habits (Clout, 2001). Hence, in many cases, native vegetation is under threat by both animal and plants pests.

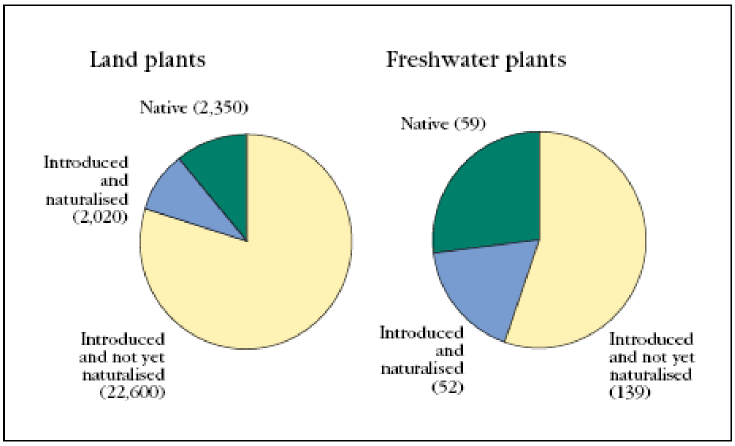


Figure 1.4 Native, introduced and naturalized land and freshwater plants in New Zealand. (Source: Williams and Cameron, 2000, pg. 8, used with permission).

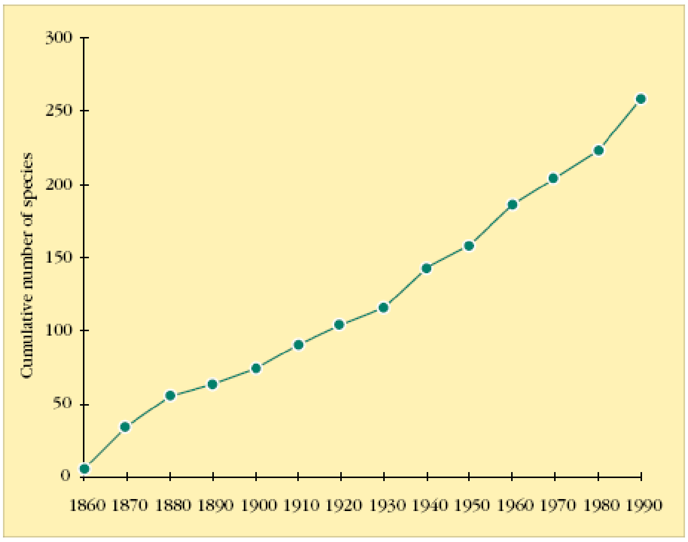
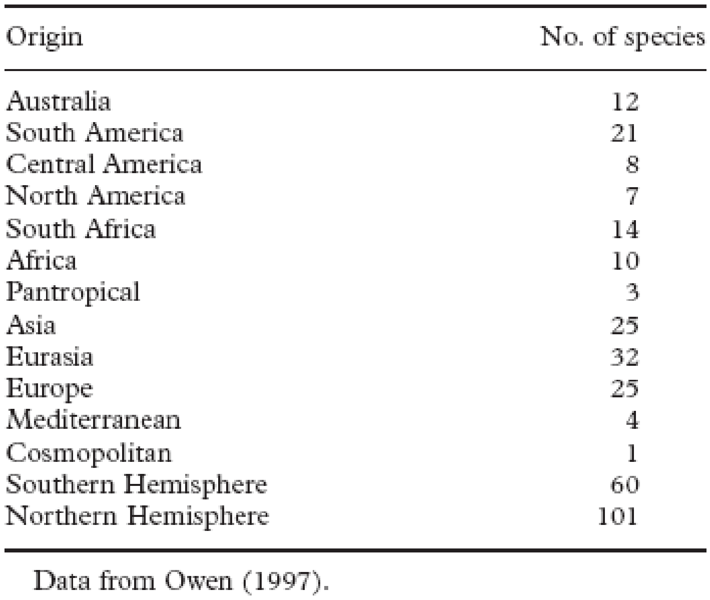


Figure 1.5 Cumulative number of introduced species that have become invasive in New Zealand. (Source: Williams and Cameron, 2000, pg. 8, used with permission).

As shown in Table 1.1, 63% of problem weeds in New Zealand originate from the Northern Hemisphere, and 37% from the Southern Hemisphere, with the largest pool of weeds arriving from Eurasia, Europe, Asia and South America, and is indicative of the trade and migration patterns that foster importation of non-indigenous species.



Origin	No. of species
Australia	12
South America	21
Central America	8
North America	7
South Africa	14
Africa	10
Pantropical	3
Asia	25
Eurasia	32
Europe	25
Mediterranean	4
Cosmopolitan	1
Southern Hemisphere	60
Northern Hemisphere	101

Data from Owen (1997).

Table 1.1 The origin and number of the major pest plants in New Zealand. (Source: Williams and West, 2000, pg. 427, used with permission, based on data from Owen, 1997).

Over 70% of the invasive weeds were deliberately introduced into New Zealand as ornamental plants, and lag periods may have been experienced before they emerged as invasives (Williams et al., 2002). A further 12% were originally introduced into agricultural, horticultural or forestry systems. Only a minor 11% can be attributed to accidental introductions, which indicates that there was little awareness of the significant impacts that these species could have on native flora and fauna, once naturalised. In the Auckland region alone, a total of 615 introduced plants are known to have naturalised, a figure thought to be unmatched by any other city in the world, with a rate of four new species naturalizing per year (DoC, 2000). Plates 1-4 show some common invasive environmental weeds in New Zealand.

Plate 1.1 *Tradescantia fluminensis*, Wandering willie (DoC, 2009)

Plate 1.2 *Zantedescia aethiopica*, Green goddess (Lewis, 2009)

Plate 1.3 *Plectranthus ciliatus*, Plectranthus (ARC, 2009)

Plate 1.4 *Vinca major*, Periwinkle (Plant Protection Society, 2009)

Plates 1.1-1.4 show a few common examples of perennial environmental weeds in New Zealand which have varying impacts on native ecosystems and other ruderal or disturbed sites. (Source: All images from the Weedbusters

website: http://www.weedbusters.org.nz/weed_info/weed_list.asp?FilterLetter=a, 2009, used with permission).

Work done by Duncan and Williams (2002) provides the evidence that selected families and genera naturalise in New Zealand at higher rates, particularly if they have species of the same genus within the native vegetation of New Zealand. Hence the historical trends of species in various taxonomic groups can be used to identify selected families and genera that pose higher risk of naturalisation and which should be taken into account in weed risk assessments. Introduced species in these genera may have similar traits with their native relatives that pre-adapt them to the New Zealand environment.

Multiple species have been identified as threatening to New Zealand's native biodiversity, of which a few of the worst are *Tradescantia fluminensis* (Wandering jew), *Hedychium flavescens* (Kahili ginger), *Ageratina ripens* (Mistflower also reported by Zancola et al., 2000), *Araujia sericifera* (Mothplant), *Asparagus scandens* (Climbing asparagus), *Clematis vitalba* (Old man's beard) (Timmins and MacKenzie, 1995). These species amongst others impact through edge, ground cover, gap and canopy infestations. For instance, *T.fluminensis* attains high infestation levels in much of the lowland forest remnants in the North Island (Timmins and MacKenzie, 1995) and reduces invertebrate abundance (Toft et al., 2001). *Asparagus scandens* also acts similarly to impede regeneration of native seedlings and by smothering and strangling understorey shrubs and saplings, in both open sunny and deep shade and damp or dry forest (Timmins and Reid, 2000).

Preventing such invasive species from entering New Zealand via effective border control is the ideal. Border control involves the management of risks from legal, illegal and accidental introductions. The New Zealand Biosecurity Act 1993 and the Hazardous Substances and New Organisms Act 1996 (HSNO) provide the legal framework for managing these risks (DoE, 2000 and Williams et al, 2002). Inevitably however, where there is inadequate control or where the invasion is not easily controlled, species will continue to establish and spread once they have naturalised.

1.3.1 Influence of land-use change and climate change

In terms of land-use change, based on results of the study by Timmins and Williams (1991), on 234 lowland forest and scrub reserves in Auckland, Gisbourne, Egmont, East Taranaki, Taumaranui, Wairarapa, Wellington, and the Marlborough Sounds, it appears that the most important land use-related reserve characteristics to influence the number of invasive pest plants are proximity to towns, distance from roads and railway lines, human use, reserve shape, and habitat diversity. Accidental spread of invasive plants needs to be minimised in order to protect these reserves along with on-going control mechanisms (Timmins and Williams, 1991).

Sullivan et al. (2005) report that coastal forests in New Zealand are under increasing pressure from the impacts of new subdivisions, especially in Northern New Zealand, where weeds escape gardens to infest neighbouring bush. Coastal forests near old and high density settlements were found to be the weediest (www.forest-bird.org.nz/magazines/01Nov/weeds.asp). Settlement characteristics such as housing age, density, proximity and garden species diversity explained a high 70% of the variation in the diversity of weeds found in adjacent forests. This study indicates that while the weediest areas are near older settlements, new subdivision developments opened those areas and adjoining natural vegetation to the risk of invasive pest plants establishing and spreading unchecked in the same way. The report also recommended that as a result, new subdivisions should be prevented from areas near important conservation reserves. Williams et al., 2002 report that herbs (e.g. *Tradescantia fluminensis*) and vines (e.g. *Araujia sericifera*) have a 17% and 36% probability of invading forested areas respectively and a 64% and 58% probability respectively of invading scrubland and grassland. This indicates that the risk to lowland scrub is higher than for forests from invasive pest plants of the herb and vine forms and also validates the study of potential future risks posed by selected species of these forms, as proposed by this research.

The important link to land-use change via land transitions to new residential subdivisions in proximity to areas of native biodiversity is critical to this research, in combination with climate variability and change. It is expected that this thesis will contribute to a better understanding of the spatial context of such changes for biosecurity decision-making and planned policy-orientated adaptation responses.

In terms of considering climate variability and change on New Zealand landscapes, the IPCC (1998) states that climate scenarios in the Australasian region indicate that temperature increases for 2030 are projected to be similar to that for Australia, of 0.3-1.4^{o}C and rainfall changes of up to 10% in magnitude. There is a possibility of increases in westerly winds leading to precipitation increases in the west and decreases in the east (IPCC, 2007b). Climate change is projected to interact with change in invasive species and habitat fragmentation, particularly in lowland habitats in New Zealand (IPCC, 2007b). Little work has been done to date on assessing the impacts of climate change on New Zealand species or native ecosystems, with the exception of the alpine zone (Halloy and Mark, 2003).

1.3.2 The policy context and assessment needs

Planning for adaptation to the effects of climate and land-use changes is a significant challenge to biosecurity and biodiversity conservation in New Zealand. As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), New Zealand has international obligations to take precautionary and anticipatory measures to prevent or minimise the adverse effects of climate change on our environment [1] and [2]. Concomitantly, the Resource Management (Energy and Climate Change) Amendment Act 2004, introduced into Part II of the Resource Management Act (RMA), requires particular regard to be given to the effects of climate change (section 7(i)) [3]. Integrated assessment tools provide resource managers and policy-makers with some of the necessary capabilities, to meet these regulatory requirements. Further to this, coordinated and flexible adaptation mechanisms will need to be fostered by mainstreaming climate change (and land-use change) considerations into existing decision-making contexts for resource management at central and local government levels.

As a signatory to the Convention on Biological Diversity (CBD) (DoC, 2000), and the United Nations Framework Convention on Climate Change (UNFCCC) among others, New Zealand has international obligations to prevent the introduction of, and undertake control and eradication of, all alien species which threaten ecosystems, habitats or species. It is also concomitantly obliged to take precautionary and anticipatory measures to prevent or minimise the adverse effects of climate change on our environment (MfE, 2001). The Biosecurity Strategy for New Zealand, released in August 2003 (The Biosecurity Council, 2003), comes as a part of our responsibility under the CBD. However, it does not mention due consideration being paid to climate and land-use change into the future, even though invasive species are likely to be more sensitive to anticipated climate change than native species (McGlone, 2001). The 2005 Review of the Biodiversity Strategy has increased the level of importance given to integrated assessment of effects of climate change, with particular respect to invasive species responses to climate change that in turn impact native biodiversity in New Zealand.

There is therefore, recognition by policy-makers of the need for capability in integrated assessment, which in this thesis relates to the *combined* effects of land-use change and climate change. This gap in risk assessment of current and potentially invasive species must be addressed if we are to understand the extent of potential risk from environmental weeds, and develop appropriate adaptation/response strategies. The Landcare Research report ‘Linkages Between Climate Change and Biodiversity’ (McGlone, 2001) states the following points:

> *“6. Potentially the most serious and pressing problems arise through the interaction of climate change with pre-existing threats to the biota. The most important involve pest and weeds, and the following outcomes are likely: (i) establishment of more invasive and damaging pests and weeds; (ii) further expansion southwards of already present exotic organisms;*
>
> *8. ... However, future or present climate change is rarely taken into account when biodiversity issues are discussed and strategy formulated.*
>
> *9. ...genuine long-term ecological frameworks and strategies that explicitly factor in climate change and global change are badly needed.”*

New Zealand lacks the necessary baseline distribution maps of its environmental and agricultural weeds at a national scale and so information on whether established weeds have reached their niche potential limits is incomplete (Dr Theo Stephens, DoC, personal communication, 2003). More comprehensive mapping of present distribution of all major invasive pest plants will be crucial in providing a baseline from which to measure temporal change in any integrated or risk assessments.

Both for New Zealand and at a global level, integrated assessments of the *combined* effects of climate variability and change and land-use changes on species are in an embryonic stage (for example, Dirnböck et al., 2003 on alpine vegetation). Furthermore, no such spatially-explicit and scenario-based assessments are available for invasive environmental weeds in New Zealand landscapes. Consequently, it is expected that this thesis will contribute original knowledge towards:

(1) Understanding the relative effects of climate and land-use changes on invasive species; and
(2) Methods for implementing integrated assessment for a single species, and risks posed to native biodiversity particularly at the landscape-level.

1.4 Case study focus

This thesis takes a case study approach to implement an integrated assessment using species distribution modelling methods. The focus is on the herbaceous trailing ground cover invasive plant *Tradescantia fluminensis* (heretofore referred to as *Tradescantia* also).

Tradescantia was chosen primarily for the following reasons: there is an experimentally derived threshold minimum temperature to which it is sensitive in terms of associated frost resistance and damage (a physiological threshold); reproduction is vegetative, and dispersal is directly linked to humans and waterways which simplifies modelling of the species distribution, as interactions with other influential dispersal agents like birds and wind, do not need to be modelled; there are 1312 observations available for *Tradescantia* at a national level covering a wide range of suitable habitats, so that the possibility of falsely classifying an area as unsuitable is reduced, in the modelling exercise; invaded habitats are related to disturbed vegetation and intact indigenous vegetation, both of which can be discriminated from land cover/land use spatial data for modelling;

and *Tradescantia* growth responds positively to nitrate nutrient enrichment (associated with disturbances in urban areas, pasture fertilisation, riparian zones and other disturbed places). Climate change, land-use change through fragmentation and changes in urbanisation patterns and extent and nitrate nutrition all are associated with global change processes, and therefore, it is likely that *Tradescantia* spread will be facilitated by these processes into the future. Further literature review of the species will be carried out in Chapter 2.

The case study landscape chosen was the Western Bay of Plenty and Tauranga, mainly because the land-use change strategic planning in the sub-region is one of the most advanced (in a policy and implementation context) of any region in New Zealand. This allows the development of the land-use change scenarios to be developed with more plausibility given the high level of spatial planning and number of spatially-explicit constraints on urban development in this sub-region.

1.5 Research and Thesis Development

The central research question posed by the thesis is:

What are the projected combined effects of climate change and land-use / land cover change on invasive plants which pose a threat to biodiversity?

As described above, this research project aims to undertake a spatially-explicit assessment of climate and land-use changes at national and landscape-levels by using *Tradescantia fluminensis* as a case study species. To meet this aim, six objectives were identified, as outlined in Section 1.5.1.

1.5.1 Research Objectives and Tasks

Objective 1: To discuss the specific characteristics which make *Tradescantia fluminensis* (Vell.) invasive, in order to establish the basis for selecting the various species-environment relationships used in the species distribution modelling, by:

- reviewing available published and un-published literature in the form of journal publications, books, technical reports, herbarium records (in particular resources available with Landcare Research, New Zealand);
- identifying and consulting with a local government agency (e.g. regional, district and city councils) as a basis for implementing the research at the regional scale.

Output: identified pest plant species for case study analyses at a regional scale.

Objective 2: To develop the functional species-environment relationships, between the identified pest species, climate parameters and land use/land cover attributes, as a basis for spatial modelling of *Tradescantia*'s distribution, by:

- reviewing accessible unpublished literature in the form of in-country agency reports, or research findings for *Tradescantia*;
- accessing on-line databases specific to plants or pest plants;
- using the LENZ climate data, correlate within a GIS framework, current 'presence-only' geo-referenced data for *Tradescantia*[3] with climate variables[4];
- using the Land Cover Database 2 (LCDB2) (Ministry for the Environment) and ECOSAT riparian data (supplied by Environment Bay of Plenty)[5], explore the association of variables within a GIS framework, against current geo-

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[3] Obtained from the Department of Conservation BioWEB database (contact Clayson Howell).

[4] The climatic surfaces and land data are available through the Land Environments of New Zealand (LENZ) database. These data have been obtained by IGCI and are available for PhD research by the candidate for Landcare Research (Leathwick et al, 2003).

[5] Obtained from the Ministry for the Environment, MfE, and Environment Bay of Plenty, EBoP respectively.

referenced presence-only data for *Tradescantia* with land cover types.

Output: modelled relationships between pest species, climate and land use types.

Objective 3: To model the species distribution[6] of *Tradescantia fluminensis*, and to provide a baseline for comparing the effects of future climate change on species distribution, by:

- reviewing and identifying appropriate species distribution modelling methods to be implemented with *Tradescantia*;
- implementing the modelled relationships (from Objective 2) within a GIS framework;
- validate the range based on observational data on pest distribution.

Output: spatially-explicit baseline map of potential species distribution of *Tradescantia* at the national and landscape-levels.

Objective 4: To develop a suitable approach for creating plausible scenarios of land-use/land cover change that incorporate change to suitable habitats, disturbances, and dispersal for *Tradescantia*, as a basis for assessing future effects on the species distribution at the landscape-level, by:

- translating regional biodiversity targets into spatially explicit changes in suitable habitats to 2050;
- collecting land-use/land cover spatial data and information that incorporates future region-specific urban development projections, based on regional policy directions/targets for land-use;
- conducting proximity analyses (using GIS tools) to link urban and peri-urban expansion, and road and stream networks, as proxies for disturbance; and
- integrating these changes into coherent 'storylines' of spatial changes or land-use change scenarios to 2050.

Output: alternative land-use/land-cover change scenarios at the landscape-level in the case study area to the time horizon 2050.

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[6] The current potential species distribution as constrained by existing land use types.

Objective 5: To develop plausible scenarios of climate change, as a basis for assessing future effects on *Tradescantia*'s distribution at a national and landscape-level, by:

- reviewing the literature on climate change, and scenario-development;
- using the CLIMPACTS Open Framework Modelling System[7] to create plausible future climate and climate change scenarios based on selected Global Climate Models(GCMs) and Greenhouse Gas Emissions scenarios (using SRES scenarios) to the time horizon 2050;

<u>Output:</u> a selection of alternative climate change scenarios to the time horizon 2050 at the national and landscape-level.

Objective 6: To implement the species distribution methods at the national and case-study levels, as a basis for assessing the possible effects of projected changes in climate and land-use/land cover on *Tradescantia*'s future distribution, by:

- using presence-only data on *Tradescantia* with the climatic variables at the national level, using the species distribution models selected through Objective 3;
- incorporating the land-use/land-cover scenarios and climate change scenarios at the landscape-level and implement the species distribution models using the presence-only dataset for *Tradescantia*;
- conducting sensitivity analyses to test and validate the model system by comparing model results to observational data on plant distributions and land-use changes within the region.

<u>Output:</u> integrated potential future species distribution maps for *Tradescantia* at the national and landscape-levels.

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[7] Developed under the CLIMPACTS Research Programme, lead by the International Global Change Institute (IGCI), in collaboration with seven other New Zealand-based institutions: the National Institute for Water and Atmospheric Research (NIWA), Landcare Research, Crop and Food Research New Zealand, School of Environmental and Marine Sciences (SEMS) at the University of Auckland, HortResearch, and AgResearch.

Objective 7: To identify areas of increased risks of adverse impacts from *Tradescantia* under future scenarios of climate and land-use/land-cover changes, with particular reference to urban/peri-urban forest fragments of biodiversity significance in the case-study region, as a basis for model evaluation, by:

- comparing the changes to habitat suitability for *Tradescantia* under each of the integrated scenarios from Objective 6, per category of protected area type: reserves network, Environmental Enhancement areas, priority landscapes, sites of ecological significance and Department of Conservation protected areas;

<u>Output:</u> An assessment using the integrated model and an evaluation of its usefulness in identifying changes in risks from *Tradescantia* for areas of conservation priority.

1.5.2 Methodological Approach

In general, an interdisciplinary approach is required to implement the thesis research. It is envisaged that knowledge and methods from such disciplines as terrestrial invasive species ecology, landscape ecology and climate and land-use change scenario development, species distribution modelling and conservation biology will be usefully integrated. Tools for spatial analysis, such as geographical information systems (ArcGIS 9.2, by ESRI International and IDRISI 11.0, by Clark Labs, Clark University), will be central to the research. Such tools will be used to link land-use activities to abiotic factors, such as climatic and land variables (Longley et al., 1999 and DeMers, 2002), and other natural and human-settlement-related features to provide a unifying framework for analysis and interpretation. Figure 1.6 shows the general conceptual linkages developed through the integrated assessment methodology. Five major steps were undertaken as a part of the methodological approach.

Firstly, species level data on known climatic and physiological limits at a global scale and within New Zealand were used from published and un-published literature, as well as from ongoing experimental work being carried elsewhere in New Zealand (for example, as being undertaken by Landcare Research), in order to specify exclusion thresholds for the distribution of *Tradescantia*. A selection of environmental variables were selected for implementation in the species distribution modelling methods and explored against the presence-only dataset for the species.

Secondly, information gathered on species-environment associations (at national and landscape-levels) was used to estimate potential baseline of *Tradescantia* distribution. This baseline potential species distribution pattern was used to compare with future change scenarios. Two modelling methods were selected based on their suitability for ‘presence-only’ distribution data: BioCLIM in the DIVA-GIS version 5.2 (Ecological Niche analysis) (Source: http://www.diva-gis.org/), and BioMapper version 4.0 (Ecological Niche Factor Analysis, ENFA) (programme developed by Alexandre Hirzel, available at: http://www2.unil.ch/biomapper/).

Thirdly, the land-use scenarios were developed to spatially assess suitable habitats and indicators of disturbance at the landscape-level. This also required landscape-level analysis within a GIS to assess habitat/forest fragment variables such as perimeter-area, connectivity of fragments and proximity to roads, tracks and built areas to assess invasibility in existing and new areas by *Tradescantia*, under various land-use and climate change scenarios. Three land-use change scenarios were developed based primarily on spatial changes to the urban areas by 2050 and these were: (1) no net change scenario (2) SmartGrowth scenario and (3) ‘Spill-over’ Growth scenario, for the Western Bay of Plenty-Tauranga sub-region. Scenario (1) was based on current Land Cover Database 2 (LCDB2) for New Zealand, and land use planning projections to 2050, developed under the Smart Growth Strategy were utilised for scenarios (2) and (3).

Fourthly, within the CLIMPACTS Open-Framework Modelling System (http://www.waikato.ac.nz/igci/climpacts/), climate change scenarios produced by General Circulation Models (GCMs)[8] were scaled with time-dependent changes in global temperature derived for a range of greenhouse gas emissions scenarios for different climate sensitivities. These patterns of climate change are used to perturb spatial climatologies available through the LENZ database (Leathwick et al., 2003; IPCC, 2001). These modified climate surfaces were used to project the future distribution scenarios of *Tradescantia*.

Fifthly, the integrated scenarios of climate and land-use changes were implemented using BioMapper and GIS at the landscape-level. Model specification was done via multiple information sources including published literature, databases, and stakeholder consultation (relevant regional pest plant practitioners) which assisted in conceptualisation of the study and selection of variables - in terms of the specifications on the species, its niche, growth requirements and limiting factors, and habitat characteristics that are relevant to the region of interest and to end-users. Model-based spatial analyses were carried out for baseline and future scenarios within the integrated model system.

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[8] GCMs are three-dimensional mathematical models that represent physical and dynamical processes that are responsible for climate (IPCC, WGI, 2001).

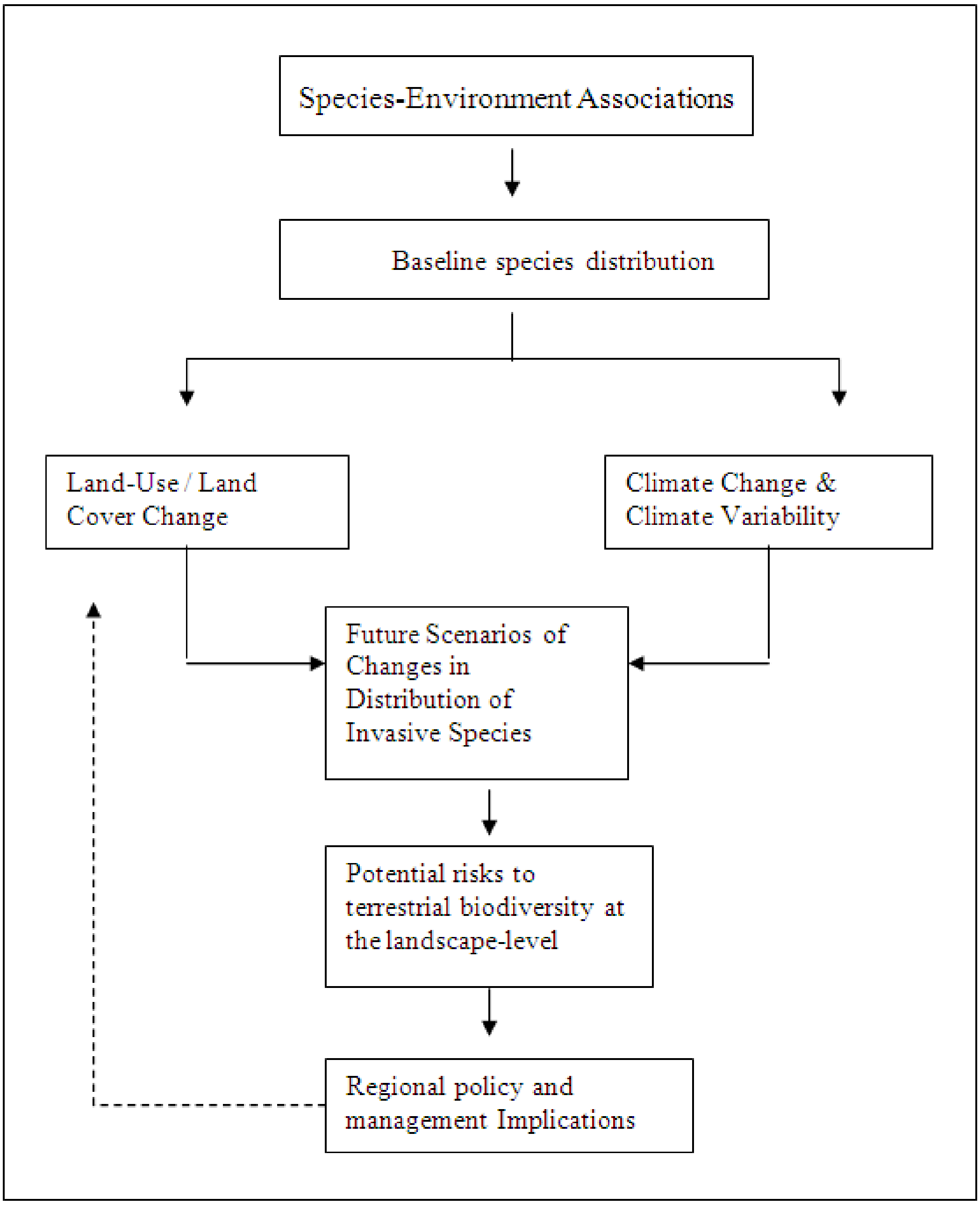

Figure 1.6 A conceptual schematic of the proposed research study.

1.5.3 Research contribution

This thesis will be an original contribution to knowledge for a combination of reasons:

1. This is the first research investigation of climate change and land-use change effects to be undertaken for *Tradescantia fluminensis* in New Zealand, at conceptual, methodological and practical levels. The results will provide a basis for policy-relevant and spatially-explicit information that can be used by decision-makers for other widespread and high impact invasive plants.
2. The methodological approach developed for the study is an integration that involves a land-use change component, climate change component and a landscape component and is unique for New Zealand.
3. While the primary aim was to contribute to understanding on invasive plant combined effects, the species distribution modelling is also user-orientated. It is relevant to policy-makers and planners, particularly in biosecurity-biodiversity and protected area management.
4. While the species distribution modelling is developed for a New Zealand landscape in an urbanising sub-region (Western Bay of Plenty-Tauranga, Bay of Plenty Region), it can be generalised. The model would be appropriate to any region where similar data exists, i.e. any region in New Zealand or globally.

1.5.4 Thesis Outline

Chapter 1: Topic overview and thesis Organisation

This chapter will provide an overview of the issues relating to invasive plant pests at the landscape-level, their threat to native biodiversity, and the effects that climate change and land-use change are expected to have on invasive plant pests, as well as the scale of the invasive pets plant problem in New Zealand. It provides the rationale for the present study and its significance, as well as a statement of the research objectives and tasks that are proposed.

Chapter 2: Relationships of climate and land use to the distribution of *Tradescantia fluminensis* (Vell.)

This chapter provides a detailed review of the ecology of *Tradescantia fluminensis*, with particular coverage of the physiological, climatological and disturbance-related factors influencing its growth and distribution, and the development of the functional relationships between climatological parameters and land-use/land cover attributes. It will therefore provide the results for Objectives 1 and 2.

Chapter 3 Modelling the species distribution of *Tradescantia fluminensis*

This chapter will address the generation of the baseline distribution (potential distribution) of *Tradescantia fluminensis* using the climatic and land-use limiting (exclusion factors) derived in Chapter 2. This chapter will review the methods in use for species distribution modelling, use the available presence-only distribution data, and present the results of the baseline mapping along with model validation results, hence addressing Objective 3.

Chapter 4 Land-use change scenarios at the landscape-level

This chapter will cover the development of land-use change scenarios at the landscape-level, to be used in the integrated species distribution modelling in Chapter 6. Particular attention will be paid to future regional land-use developments that relate to the creation of new suitable habitats, disturbance sources and dispersal of *Tradescantia*'s invasive plant propagules. The scenarios are developed for the case study area: the Western Bay of Plenty and Tauranga. Methods for land-use scenario generation will be reviewed, and region-specific land-use change analyses results will be presented, addressing Objective 4.

Chapter 5 Climate change Scenarios

This chapter will cover the development of the climate change scenarios within the framework of the integrated species distribution modelling undertaken in Chapter 6. It will look at the current state of science in climate change modelling for spatially-explicit assessments. It will discuss the selection of appropriate

Greenhouse Gas emissions scenarios and Atmosphere-Ocean Coupled General Circulation Model (AOGCM) patterns, and give a description of the climate change scenario generation capabilities within the CLIMPACTS Open-Framework Modelling System, used to generate the spatial scenarios in this study, addressing Objective 5.

Chapter 6 Integrated species distribution model for *Tradescantia fluminensis*

This chapter will deal specifically with the integration of the invasive species distribution model (Objective 3), with climate change and land-use/land cover change scenario generators (Objective 4 and 5) to produce the scenarios of change for each of the selected invasive pest plant species and sensitivity/validation analyses (Objective 6), using BioCLIM (climate-only at the national-level) and Biomapper (climate only at national-level; climate and land use at the landscape-level). A review of literature specific to integration and modelling of species information and landscape-level information will be included along with the scenarios generated by the integrated species distribution models.

Chapter 7 The effects of climate and land use change: Major findings and conclusions

This chapter will evaluate and assess the combined effects of land-use change and climate change on invasive pest plants based on the integrated model. It will address Objective 7 in identifying areas of increased risk of adverse impacts from the selected invasive pest plants, given the future scenarios under climate and land-use change. It will also evaluate the usefulness of the integrated model for the assessment and provide a thorough discussion of the integrated assessment process and its outcomes and relevance for decision-support for biosecurity. It will include the conclusions relating the major objectives of the project.

2 Chapter 2: Relationships of climate and land use to the distribution of *T.fluminensis*

2.1 Introduction

This chapter provides a review of the literature on *Tradescantia fluminensis* (Vell.). The review focuses on its invasive ecology and its relationships to climate, land use and landscape-level habitat, and to natural and human-induced disturbance. It derives functional relationships to these factors that influence the spatial distribution of *Tradescantia* globally and in New Zealand. The species-environment relationships are integrated in the spatially-explicit baseline and future species distribution modelling undertaken in Chapters 3 and 6.

2.2 General Species Description

Tradescantia fluminensis (Vell.)[9], synonymous with *Tradescantia albiflora* (Kunth), is a frost-sensitive herbaceous trailing monocot, with a perennial life cycle. The native range of the species is in South East Brazil and Argentina, mainly in moist forests (Cabi, 2004, In: Global Invasive Species Database, source: http://www.issg.org/database/species/ecology.asp?si=497&fr=1&sts=sss). *Tradescantia* is a 'symptomatic invader', in the sense that it requires disturbance (i.e., increased light and soil nitrogen) for establishment at a local level. *Tradescantia* spreads primarily by vegetative reproduction, with no seed set observed in New Zealand (Healy & Edgar 1980). It is considered one of the many invasive species within the Commelinaceae family of plants worldwide. Common names for the species include: wandering jew, wandering willie, small-leaf spiderwort, wandering creeper, white flowered wandering Jew, spiderwort, nohakata karakusa, and Vandrande Jude (Global Invasive Species Database, source: http://www.issg.org/database/species/ecology.asp?si=497&fr=1&sts=sss).

The species grows by vegetative reproduction from plant propagules. In its native range it can produce seed from bisexual flowers (Faden and Hunt, 1991). Flowers

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[9] This species will be referred to as '*Tradescantia*' throughout the thesis, for ease of reading.

are produced in New Zealand typically between August and November. Once established, it can continue in perpetuity if undisturbed within a forest stand. Vectors that facilitate spread, in approximate order of importance are: humans > streams > cattle > road machinery (Standish, 2002). In most locations, *Tradescantia* grows in high biomass ground cover mats comprised of interlaced vertical leafy shoots on horizontal leafless stems held to the substrate by abundant fine roots that also form at aerial nodes within the mat (Global Invasive Species Database, source: http://www.issg.org/database/species/ecology.asp?si=497&fr=1&sts=sss). High biomass swards can persist indefinitely and plants can re-sprout from fragments of 1 cm length (Kelly & Skipworth, 1984).

Tradescantia is typically an environmental weed of modified and natural areas and does not appear to be a significant weed of crops (CABI, 2004, In: Global Invasive Species Database, source: http://www.issg.org/database/species/ecology.asp?si=497&fr=1&sts=sss), except within its native range. In New Zealand, the Department of Conservation has assigned *Tradescantia* a weed ranking of 25 (where 0 indicates minimal impact and 34 indicates maximal impact), based on its ‘effects on the system’ and ‘biological success’ (See Plate 2.1 of an invading *Tradescantia* sward penetrating a lowland remnant). This is a high impact compared with scores of 22 (*Vinca major*) and 23 (*Selaginella kraussiana*) for other mat-forming weeds in New Zealand (Owen 1997). The species is known to increase forest litter decomposition and alter nutrient availability, effects that could have an influence on the long-term viability of many of the *Tradescantia*-invaded podocarp-broadleaf dominated forest remnants in New Zealand (Standish, 2004).

Plate 2.1*Tradescantia fluminensis*, the case study species. It is a trailing perennial herb. In disturbed remnants with poor vegetation condition and canopy cover, *Tradescantia* can become the dominant ground cover species, as shown in the middle insert photo. The plant produces flowers but does not set seed in New Zealand and is reproduces effectively by vegetative plant fragments (Standish, 2004). (Source: Roy et al., 2007, pg. 140, used with permission).

2.2.1 Nomenclature and Taxonomy

Tradescantia belongs to the large Commelinaceae family (with approximately 650 species; Hunt, 1993), distributed mainly in the tropical to subtropical regions of the world. The family contains at least 12 invasive species that are primarily invasive in cropland and disturbed habitat, and at least 28 weedy species, which can spread rapidly in disturbed habitats in their native range (Burns, 2006). There are several other species of the Commelinaceae family which are similar to *Tradescantia* but not to be confused with it, including: the *Callisia spp., Commelina spp., Dichorisandra spp., Tradescantia crassula,* and *Tradescantia zebrina.* Importantly, not all congeneric species of Commelinaceae are invasive (Burns, 2006).

The Commelinaceae belong to the Order Commelinales, containing three families (Hutchinson 1959). There are no native Commelinales in New Zealand (Moore & Edgar 1970). The Liliales are the closest relative of the Commelinales with native representatives, e.g. Astelia, Collospermum, Ripogonum (Hutchinson 1959; Moore & Edgar 1970), but these are morphologically quite different from *Tradescantia*. As a result, *Tradescantia* is taxonomically distinct from native resident species, which, if equal to ecological distinctiveness, could explain some of its success as an invader in the absence of any congeneric competitive species (Williamson, 1996).

According to Standish (2002), it is feasible that only one well-adapted genotype of this species exists in New Zealand. *Tradescantia virginiana* L. has been collected as a ‘persistent garden outcast’ on wasteland in Christchurch on the South Island of New Zealand, but has not established in native communities (Healy & Edgar 1980; Landcare Research Herbarium 2001, In: Standish, 2002). Similarly, *T. cerinthoides* (Kunth.) is listed as an exotic species of New Zealand but has not yet naturalised (Landcare Research Herbarium 2001, In: Standish, 2002).

2.2.2 Species Ecology of *T.fluminensis*

The ecology of *Tradescantia* is reviewed with respect to the two distinct dimensions widely responsible for observed invasive species distributions at multiple scales (1) invasiveness, i.e. species-related physiological, morphological or other characteristics that make a species invasive; and (2) invasibility, i.e. habitat-related characteristics which make a defined geographic area vulnerable to invasion. Invasiveness determines to a large degree, the likely species *response* to changing environmental resources, biotic and abiotic gradients and various sources of disturbance. Invasibility is intrinsically linked with landform, landscape structure and configuration, which influence the spatial *availability* of these resources along various gradients (either natural or human-induced).

2.2.2.1 The species invasiveness of *T.fluminensis*

The physiology of *Tradescantia* enables rapid response to the availability of two primary resources at the local level - light and nitrogen (Kelly & Skipworth 1984a; Maule et al., 1995; Standish, 2002). This rapid response determines the subsequent impact *Tradescantia* has on native forest regeneration (Standish et al., 2001). *Tradescantia* can persist in the deep shade (down to 1.4 % of full light; Adamson et al. 1991) and can acclimate to light levels from 1%-100% (Maule et al., 1995), making it highly suitable for invasion at edge habitats, as well as some distance within habitats where light levels are lower. This light acclimation is a characteristic trait of early successional, colonising species (Bannister, 2003b), which are often subject to varying levels of resource availability and disturbance. Damp, fertile soils support dense swards of *Tradescantia* (Ogle and Lovelock, 1989; Standish et al. 2001). Timmins and Williams (1991) found that *Tradescantia* was often found on sites with high soil fertility, these sites being more likely to be regularly flooded by rivers which deposit nutrients, silt and weed propagules. This finding highlights the high invasiveness of riparian areas. There are some indications that *Tradescantia* is sensitive to humidity levels (Standish et al., 2001), and drought may limit its biomass accumulation or even its ability to establish in an area (for instance in eastern Wairarapa, Howell et al. 2000a). An alternative explanation for the absence of *Tradescantia* in areas of high annual water deficit, AWD, may be an indirect effect of the loss of suitable native habitat through native vegetation removal.

According to Standish (2002) and Duncan and Young (2000), dense *Tradescantia* swards can out-compete native ground cover and forest floor seedlings within invaded remnants, clearly responding to available resources more rapidly than the resident species. With respect to nitrate, this competitive advantage in resource assimilation was experimentally confirmed by Burns (2004), whose results found that on a nitrogen gradient, *Tradescantia* had a higher relative growth rate (RGR) than non-invasive congeners of Commelinaceae at high nitrogen availabilities. However, it did not differ from non-invasive congeners at low nutrient availabilities. Burns (2004) concluded that these findings were consistent with an invasive species strategy of rapid utilisation of available resources (also known as ‘resource plasticity’). While light, nutrients are found to increase the distribution of *Tradescantia*, experimental studies in Florida, USA, have found that low soil resources and removal of above-ground biomass (by cattle grazing) both decreased the competitive advantage of *Tradescantia* (Burns, Halpern and Winn, 2007). They also found that greater RGR and root-to-shoot ratio, along with the production of thin, soft leaves, were generally associated with invasiveness, and these characteristics are typical of *Tradescantia*.

In terms of an overall invasion strategy, Maule et al. (1995) described one possibility for *Tradescantia* at a localized level, based on their experimental work in a lowland remnant in Akaroa, on the east coast of the South Island of New Zealand. The species establishes primarily in gaps and edges, and it grows rapidly in the increased light environment, at the same time increasing nitrogen in its tissues. Once the disturbed canopy gap is closed, *Tradescantia* acclimatises to the reduced light availability and utilises the stored nitrogen (Maule et al., 1995). In the absence of any further disturbance, the established sward will reach an equilibrium biomass, turning over slowly as production of new tissue at the shoot apex is balanced by death and decay of old tissue at the shoot base. Standish (2002) goes on to explain the invasion strategy further in that the finely reticulated root system of *Tradescantia* penetrates the leaf-litter and humus layers immediately below the sward. A large part of the upper humic layer is made up of decomposing *Tradescantia* plant material; and so, the sward as a whole is likely to effectively recycle nutrients internally. Efficient recycling of nutrients within the sward coupled with the low natural input of nutrients into the system will allow *Tradescantia* to occupy a site for an indeterminate period (Standish, 2002). However, *Tradescantia* also shows many features atypical of species capable of rapid growth such as a complete reliance on vegetative reproduction (Kelly and Skipworth, 1984), the ability to acclimate to very low irradiance levels and longevity associated with low growth rate. Standish (2002a) also noted that *Tradescantia* probably does not out-compete other ground covers and forest seedlings in its native forest environment.

2.2.2.2The invasibility of habitats and *T.fluminensis*

Tradescantia is typically absent from relatively undisturbed large tracts of intact native forest (Standish, 2002). In New Zealand, such intact native forest is mainly situated in Department of Conservation protected natural areas in upland areas and higher altitudes at greater distances from the lowland-midland disturbances. Low frost resistance is also an important influencing factor on this species' distribution (Bannister, 1986) and will be revisited in Section 2.4.1.1. However, some higher-elevation site infestations, at lower temperatures, have also been recorded (New Zealand Department of Conservation BioWEB data).

In New Zealand *Tradescantia* is successful in forest remnants that have been modified as a result of disturbances such as fragmentation, and perhaps selective logging, stock grazing or possum browsing. A direct result of these modifying processes has been to increase light availability within the forest, which is of primary importance to the successful invasion of *Tradescantia* (Standish 2002a).

Other factors associated with habitat disturbance, such as increased soil nitrogen, have also contributed (Maule et al., 1995; Ogle & Lovelock, 1989). Disturbance also serves to remove competing vegetation (Grime, 1974, 1988; Hobbs, 1991). In the case of lowland podocarp-broadleaf forest remnants, cattle grazing and trampling have been particularly detrimental to native groundcover and understorey plants. If *Tradescantia* is introduced to a site that has not recovered from such disturbance then there is the potential for the invasion of unoccupied forest floor (Standish, 2002b). On the other hand, cattle and sheep may negatively affect *Tradescantia*, by intensive grazing of *Tradescantia* in localised patches (Burns, Halpern and Winn, 2007). No other major competitive or mutualistic relationships affecting the range dynamics of *Tradescantia* are recorded in New Zealand (Hampe, 2004 In: Standish, 2002).

Propagule pressure, defined as the number of propagules arriving at a site (Williamson, 1996), is a very important concept in invasion ecology (Rouget and Richardson, 2003; Bazzaz, 1986; Williamson & Fitter, 1996; Lonsdale, 1999). The probability of a species establishing is directly related to the number of propagules introduced (Martinez-Ghersa and Ghersa, 2006; Rouget and Richardson, 2003; Williamson, 1996).

2.3 Geographic Distribution in New Zealand

The introduced range of *Tradescantia*, based on reported observations of naturalised populations, includes New Zealand (Kelly and Skipworth 1984a; Standish et al., 2001), eastern Australia (Dunphy, 1991 and King and Buckney, 2000), Spain (Sobrino et al., 2002), Russia (Tolkach et al. 1990), California, North Carolina, Florida (Farr et al. 1989; Wunderlund 1998), Japan, Portugal, Uruguay, Paraguay and South Africa (Global Invasive Species Database, source: http://www.issg.org/database/species/ecology.asp?si=497&fr=1&sts=sss and Alston and Richardson, 2006).

Tradescantia was first introduced to New Zealand, in 1910 by a Manawatu farmer (Kelly and Skipworth 1984a), and was recorded as being naturalised in Awanui, Northland, soon after (Carse 1916 In: Kelly and Skipworth, 1984a). Subsequently, it has dispersed widely (Esler 1978).

Currently, the distribution of *Tradescantia* spans 11 of the 13 DoC Conservancies (Standish, 2001a) across the country. Tongariro/Taupo, Otago, and Southland Conservancies do not list *Tradescantia* as a problem weed. It has also spread to some off-shore islands, e.g. Stewart Island, Stephens Island (Brown & Rees 1995), Matiu and Mana Islands (Howell et al. 2000a), the Chatham Islands and Rangitoto Island (Susan Timmins, pers. comm.; Rachel Standish, pers. comm.; Standish, 2002). *Tradescantia* continues to invade new sites on the North Island predominantly, within the Northland, Auckland, Waikato, Bay of Plenty, East Coast/Hawke's Bay, Wanganui, Wellington and Nelson/Marlborough (South Island) Conservancies (Owen 1997).

For this thesis, data on the national-level distribution of *Tradescantia* was provided by the Department of Conservation (DoC) from their national BioWEB database, which contains distribution data for all major environmental weeds of conservation importance in New Zealand. Distribution records have been collected and contributed by numerous individuals, DoC staff, scientists, Wellington Regional Council, Porirua City Council Keysite Database, Wildlands Survey, Vigil Forest Health, Department of Conservation Masterton, Pest Plant Inventory, Environment Southland amongst others. The earliest records date back to 1962. The data were collected in a wide variety of sites, including Scenic Reserves, Forest Parks, Historic Reserves, towns and cities, many local bush sites, roadsides, river and stream banks, lakeshores, jetties, around buildings, in gardens and urban residential properties (See Figure 2.1 for the national distribution from BioWEB).

In the case study area, the Western Bay of Plenty and Tauranga, the Bay of Plenty Regional Council has collected presence-only records in addition to the BioWEB records for regional pest management purposes. This dataset is used in combination with the BioWEB records for the case study landscape. Additional points were collected by the author for known infestations in the Tauranga area. The dataset used represents ‘presence’ data only and no ‘absence’ data were recorded. This influences the methods of species distribution modelling used in Chapters 3 and 6, which will be discussed further in Chapter 3.

The BioWEB dataset had 1312 presence data points distributed across the North and South Islands, of which 931 points are found on the North Island and remaining 381 points are found on the South Island. The data points represent small patches of dense *Tradescantia* infestations in many cases, while there are a few records which indicate that the plant is growing as scattered plants in very low abundance. Where *Tradescantia* points have been recorded along streams and rivers, it is most likely that these would be more extensive patches given the high suitability of these areas for *Tradescantia*. In several locations *Tradescantia* was recorded growing near carparks, on waste dumpsites, beneath bridges, on coastal bluffs, a swamp lake edge, and beach dunes.

Since the presence records were supplied by multiple sources, the likely sampling bias associated with a single agency is reduced. Furthermore, the data includes multiple presence points on private land, in urban and agricultural areas outside the national protected areas and reserves network. The data are therefore likely to be a representative sample of the total infestations across all invaded habitats for *Tradescantia* at the national level, although they do not represent all infestations in the country. The only known exception to this is in the Christchurch and Banks Peninsula area, on the east coast of the South Island, where the Department of Conservation have reported a deficiency of presence records (pers.comm., Susan Timmins and Clayson Howell, 2007). This is also likely to be the case in Dunedin in the south of the South Island, given that *Tradescantia* is not a priority weed in the region, though it is known to be present there. A few areas have a higher density of presence points, including New Plymouth (South-west of North Island), Wellington Region (southern-most area of the North Island) and the Marlborough Sounds area (north-eastern tip of the South Island). It is most likely that this is a result of a greater sampling effort in these areas by local authorities, particularly by the Wellington Regional Council in the urban areas of Wellington, rather than an anomalously high number of presence points in these places, compared to other parts of the country. See Figure 2.1 showing place names of New Zealand used in this study, followed by Figure 2.2 showing the distribution of *Tradescantia* records/presence observations from BioWEB, at the national level in New Zealand.

The main limitation with these datasets is that at the national-level BioWEB provides a good indication of areas invaded, however, at the local landscape-level, the number of data points available is relatively small. To illustrate this, when the presence data points provided by the Bay of Plenty Regional Council (EBoP) were added to the BioWEB data for the case study landscape, the number of presence points almost doubled. Even with the extra presence points from EBoP, it is known that there are many invasion sites, particularly in the urban areas of Tauranga, Te Puke, Omokoroa, and Katikati for instance, that have not been recorded.

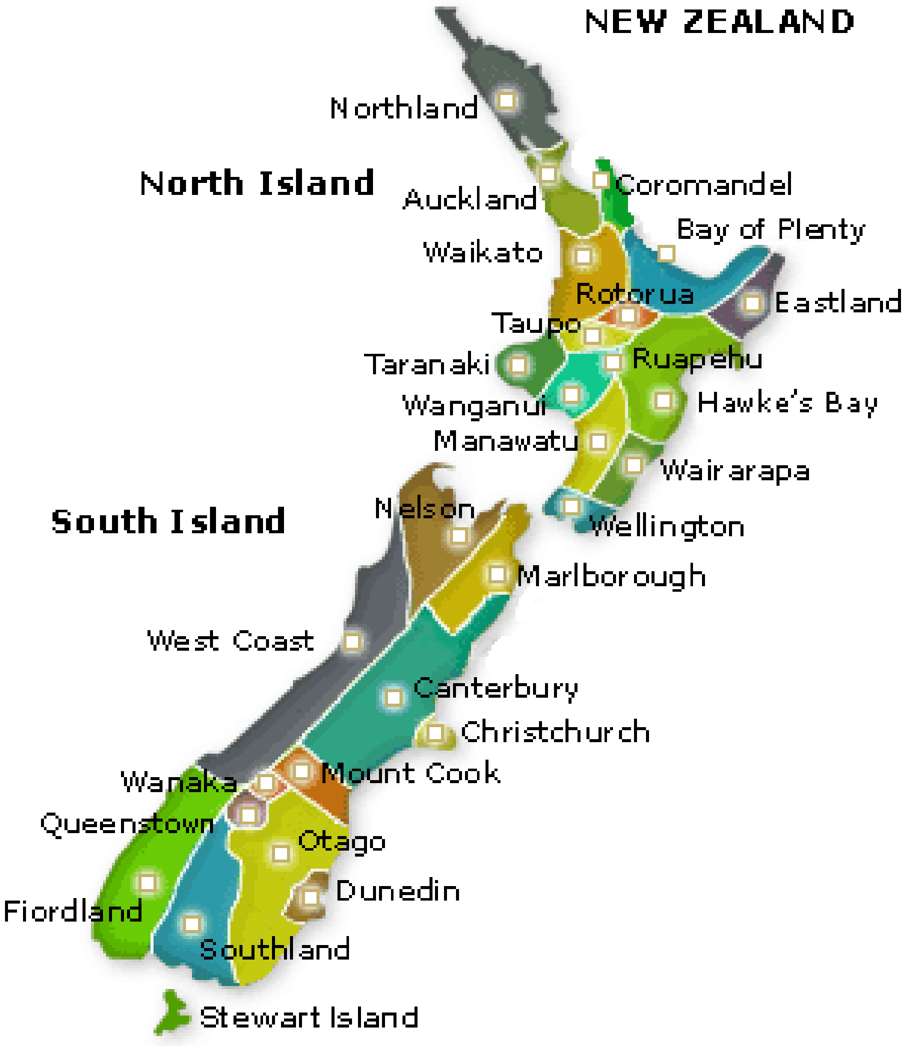

Figure 2.1 The map of New Zealand indicating place names of the major regions and cities on the North and South Islands. This map will be useful in identifying areas and places with relation to the geographical datasets used and in interpreting the various spatial maps produced as a part of the species distribution mapping in Chapters 3-6. Although not explicitly shown here, the mountain ranges of the North Island are located around Ruapehu (the Central Volcanic Plateau) and towards Eastland, Mt Egmont in Taranaki and the Southern Alps (the Southern Axial Mountain Range) on the South Island running through the central regions of the Island from Nelson-Marlborough south to Fiordland. (Source: The New Zealand Travel Guide, url: http://www.tourism.org.nz/regions.html, 2009, used with permission).

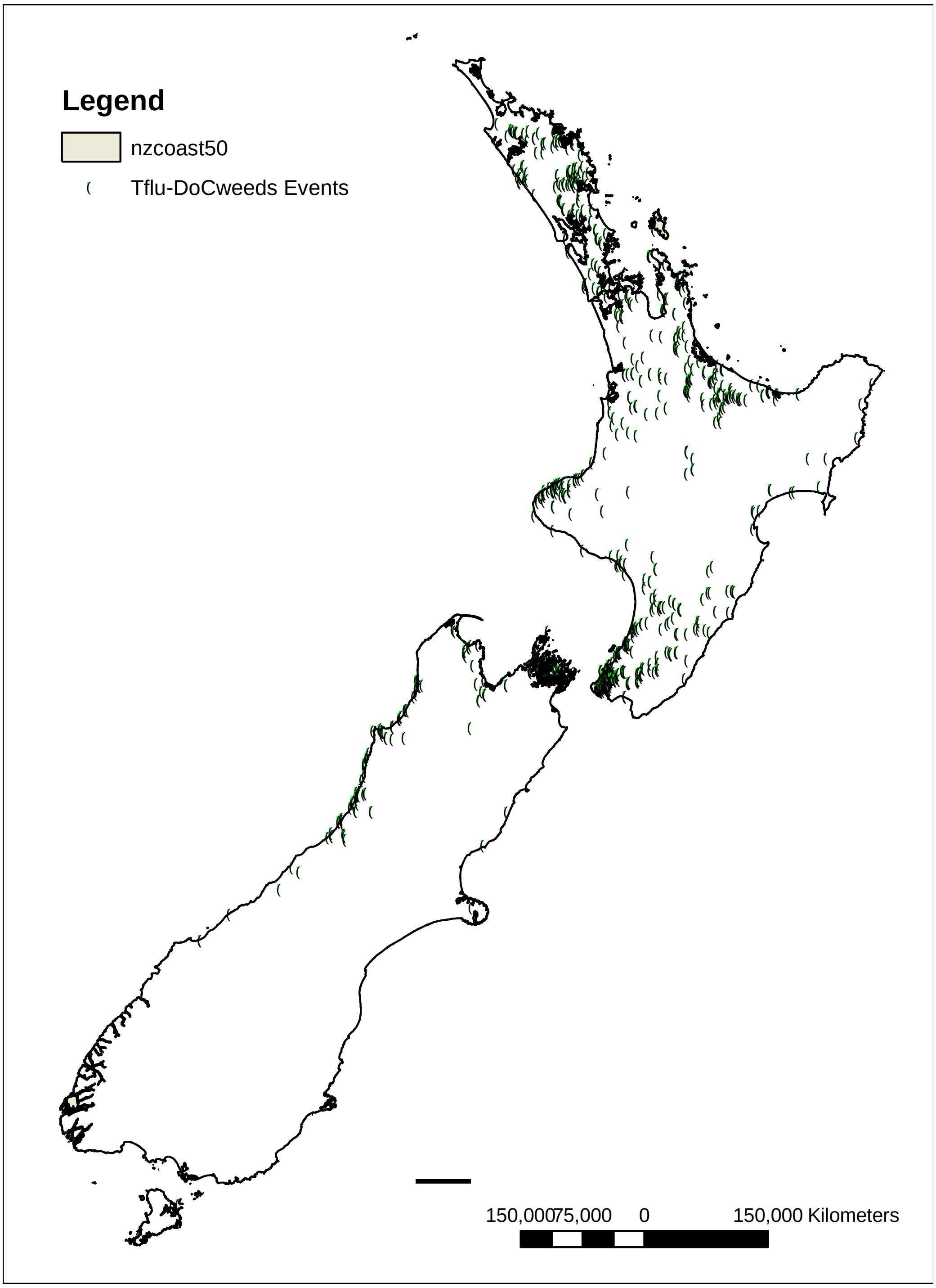

Figure 2.2 The national distribution of *Tradescantia fluminensis* in New Zealand. It illustrates a widespread distribution of the species on the North Island and a limited coastal distribution on the South Island primarily on the west coast. *Tradescantia* is present on the east coast of the South Island, although the presence records are missing for these areas. (Data Source: Clayson Howell, BIOWEB Database, Department of Conservation, New Zealand).

2.4 Species-environment relationships and the national distribution of T.fluminensis

A central thesis for species-environment relationships in plant ecology is that climate exerts the dominant control on the distribution of vegetation types and individual plant species. Smaller-scale variations in distribution may be controlled by localised or proximate features of the environment such as soil types, human activity or topography (Woodward, 1987). However, at all scales the response of the plant to climate is a crucial feature in its presence. Our understanding of the relationship between a species' distribution and environmental variables can be either eco-physiological[10] or correlative[11], and an understanding of both is necessary in studies of the climatic controls on vegetation distribution at multiple scales. It is also important that, if correlative studies are conducted to estimate species distribution, climatic parameters be selected which are physiologically meaningful or relate directly to plant dispersal and spread.

The invasibility of habitats is the product of several factors, including climate, disturbance regime, and the competitive abilities of the resident species (Lonsdale 1999). It may also be affected by the presence (or absence) of herbivores, pathogens (D'Antonio 1993; Lonsdale 1999) and mutualists (Crawley 1987; Marler et al. 1999). As a result, factors relating not only to climate, but also to the disturbance regime and propagule sources need to be factored into the analysis of the species distribution. These climatic, disturbance and propagule source-sink relationships are further explored in the following sections of this chapter, at national and landscape levels, to select suitable variables for the baseline species distribution modeling of *Tradescantia* in Chapter 3.

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[10] Based on detailed knowledge of the physiology and life history traits of plants or functional groups of plants (Stephenson, 1998)

[11] Reveal broader and often correlated relationships between climate and vegetation distribution

2.4.1 Climate and Distribution

One of the dominating factors found to regulate plant growth and survival, and therefore linked to the potential spatial distribution of a species in New Zealand, is temperature (Leathwick and Mitchell, 1992; Leathwick, 1995; Leathwick and Rogers, 1996). The spatial patterns of climate used in this study were provided by Landcare Research NZ and the Department of Conservation, through the Land Environments of New Zealand (LENZ) classification, and were derived by fitting mathematical surfaces to long-term climatic data gathered by meteorological stations throughout the country (Leathwick and Stephens, 1998).

In exploring the association between climate and plant distributions at global, national and regional scales, I assume that the distribution can be modelled based on the ambient (exogeneous) average climate conditions (Hart et al., 1995), as per studies reviewed in Chapter 3, rather than directly using microclimatic conditions, although we know that at localized sites, plants are influenced by microclimatic gradients (also Tani et al., 2001). It is also assumed, that the long-term exogenous GHG-enhanced climatic changes will shift localized microclimatic gradients with the same direction and magnitude, though this response may not be strictly linear. The effects of exogeneous climate on local microclimate can be studied through ecosystem modelling approaches linked with landscape models that incorporate various feedback mechanisms between atmosphere, soil and vegetation (He et al., 1999). However, this was considered outside the scope of this present study. Also linking Global Climate Model results at a coarse spatial scale (5kmx5km), to localised microclimatic spatial scales over a few meters, is likely to be problematic.

2.4.1.1Minimum temperatures and frost

The impact of low (minimum) temperature on plant physiology and species distribution can be readily observed for species which are grown outside their native geographic range (as in the case of invasive species). Low temperatures influence the life cycles of plants through three mechanisms: (1) by limiting the rate of a particular physiological process, (2) by cooling the plant below the non-lethal threshold temperature of such a process and (3) by cooling the plant into the lethal temperature region. Each mechanism has been demonstrated to limit the distribution of a plant species or vegetation type (Patterson et al., 1978; Larcher and Bauer, 1981; Sakai and Larcher, 1987 and Woodward, 1987). Present-day geographical limits to the distribution of native species by minimum temperature need to be interpreted carefully when investigating limits to a species' distribution, because of the likelihood of wide spatial and temporal separation between realised distributional limits and its fundamental/theoretical climatic or niche limits. Since most invasive species are successful because they have formed self-sustaining populations outside of their native range, they are ideal for testing species distribution models beyond the native range of climatic and other conditions. There are, however, some caveats which will be discussed in more detail in Chapter 3.

The ability of a species to survive low winter temperatures to a certain threshold, has been an attractive starting point for describing the climatic control on a plant's distribution (Woodward, 1987). A clear correlation appears to exist between the temperature at which the cell membrane in a plant changes from the liquid-crystalline to the gel state, and the geographical range of a number of plant species (Raison et al., 1979). Woodward (1987) explains that the implication is that irreversible cell injury occurs, probably due to reduced permeability to water diffusion across the membrane in this new gel state. The ability to resist this change at low temperature is genetically controlled, setting a finite limit or threshold below which plant survival at low temperatures is diminished. Frost damage or even frost kill may be incurred by plants (or specific parts of plants such as leaves) under sufficient levels of frost stress. However, at local levels, where plants are sheltered either by physical features such as rocky outcrops, or by overtopping vegetation ('nurse plants'), the frost tender species may receive radiation from the nurse plants' branches, which have much higher effective temperatures. These micro-habitat factors may enhance survival in otherwise unsuitable areas by providing a greater or lesser reduction in frost intensity (Osmond et al., 1987 and pers. comm., Peter Bannister, 2005).

Tradescantia is known to be a frost-sensitive species that suffers damage when exposed to frost (Maule et al., 1995). Under experimental conditions, *Tradescantia* was shown to have a 50% lethal temperature minimum (L_{50})[12] of

-4.2±0.2 ^{o}C and a freezing resistance of -4^{o}C (Bannister, 1986). Since both values can be used for frost resistance, the later value of -4^{o}C will be used in this thesis[13]. The United States Department of Agriculture (USDA) has produced a frost hardiness rating with 11 climatic zones based on mean annual minimum temperatures (Zone 1 $\leq$ -45 ^{o}C through to Zone 11$\geq$ 4.5 ^{o}C) which is used to also comparatively assess plant hardiness of many native species in New Zealand, South Africa, Australia and South America (Bannister, 2003; Bannister and Lord, 2006). The USDA frost hardiness rating of *Tradescantia* includes climatic zones 9-11, which have minimum temperatures $\geq$-6.6^{o}C. However, Bannister's freezing resistance of -4^{o}C would indicate that the species may in fact be less frost resistant than the USDA frost hardiness rating suggests.

Tradescantia's frost resistance is low by comparison to other New Zealand native species, for example *Leptospermum scoparium*, *Leptospermum ericoides*, and *Hebe albicans*. To illustrate the comparatively low frost hardiness of *Tradescantia*, the study by Bannister (2003a) is used here. Bannister undertook field studies following an extreme frost episode in 1996 in Dunedin, South Island, New Zealand. He compared frost damage[14] in several species of native trees and

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[12] L_{50} – the temperature at which 50% of the plant is damaged. Various levels of damage are used for expressing the critical temperature for frost resistance (LT). These include the lowest temperature at which plants experience no damage (LT0), the "freezing resistance" of Sakai and Wardle (1978); the lowest temperature causing initial damage (LTi), e.g., the "frost hardiness temperature" of Warrington & Southward (1995); and the lowest temperature causing 50% damage (LT50), e.g., Larcher (1970), Bannister (1990), and the "lethal temperature" of Warrington & Southward (1995). In practice, frost resistance temperatures determined for a particular species by different authors using different methods show considerable overlap.

[13] Laboratory-determined frost resistance of cut shoots or leaves has tended to overestimate the potential for frost survival with respect to the field (Pellet et al. 1981) and to artificially frozen intact plants (Stanley & Warrington 1988; Warrington & Southward 1995), but others have found reasonable agreement between the frost resistance of cut shoots and field damage during natural frosts (e.g., Bannister, 1985; Bannister & Polwart 2001).

[14] 'Frost damage' in this study refers to field damage observed in the plants. Field observations of damage were translated into a 5-point scale: from 0 (undamaged) to 1 (slight damage), 2 (moderate damage), 3 (severe damage), and 4 (apparently dead) (Bannister, 2003a).

shrubs with USDA frost hardiness ratings. From the relationship of frost damage to species frost resistance shown in Figure 2.3, it was inferred, that *Tradescantia* was likely to sustain a high damage rating of 3-4 (severe damage to apparent death) under severe frost conditions. However, where plants are not fully exposed to the frost (for instance when protected by overhead shrubs or canopy trees), *Tradescantia* may not suffer as much damage. Maule et al. (1995) also found that plants of *Tradescantia* grown under 100% irradiance outdoors, i.e. with no shade protection, showed considerable wind damage and frost damage. Frost intensity, persistence and penetration (to the sub-canopy and forest floor) are all important factors that determine the overall effect of a frost event on plant damage response. Therefore, *Tradescantia* is likely to have varying frost damage depending on the degree of exposure to air. In a uniform environment (e.g., the Southland Plains, South Island New Zealand), if temperatures are sufficiently low, all susceptible plants will be damaged, whereas in a heterogeneous environment, sheltered micro-sites (due to variations in slope, aspect, and altitude and canopy vegetation for under-storey plants like *Tradescantia*) will provide some escape from frost damage.

With respect to the New Zealand species distribution of *Tradescantia*, two effects of minimum temperature and frost are important: (1) effects on species establishment at a site, and (2) effects on species survival and the abundance of self-sustaining natural populations at a site. As an example, in Christchurch City, south-east of the South Island, New Zealand, frost is reported to damage *Tradescantia* plants severely in winter, causing localised die-back followed by re-growth and population recovery (Environment Canterbury, Biosecurity Staff, 2007).

A freezing resistance of -4 ^{o}C relates more to species survival and abundance (i.e. persistence of the plant *after* establishment), rather than being a clear determining threshold for whether *Tradescantia* will be able to establish at a site. In other words, it would be expected that freezing resistance can be used as a broad threshold for indicating where self-sustaining naturalised populations may be distributed. However, establishment of the plant may also be influenced by chance events of dispersal and localised effects of frost protection from surrounding vegetation or physical features that may attenuate the effects of the ambient ground or air minimum temperatures.

With regard to testing if Bannister's freezing resistance relates to *Tradescantia's* distribution, the study by Sakai and Wardle (1978) presents a useful technique. They tested 42 native woody trees along their freezing resistance gradient in New Zealand to the observed national geographic limits of these species and found that freezing resistance correlated well with the species' natural distributions in New Zealand (from -4 ^{o}C or warmer for the broadleaved species to -18 ^{o}C to -25 ^{o}C for the hardiest high-altitude shrubby conifers). Ecotypic[15] differences were also apparent. Air temperatures only occasionally reached or exceeded the freezing resistance of local native species, but ground frosts were more likely to affect seedlings in frosty depressions (Sakai and Wardle, 1987). It would be expected that *Tradescantia* would also be affected similarly by ground frosts to a greater degree than air frosts given that it typically does not grow above 30 cm high. *Tradescantia's* observed distribution in New Zealand was mapped against the freezing resistance threshold to explore whether Sakai and Wardle's observation of closely correlated freezing resistances and the geographical limit to the species distribution held true for this species also. If the two showed a close association then freezing resistance threshold could be applied spatially as the primary delineator of suitable and unsuitable areas at the national scale (both under baseline and future climate scenarios)[16]. Note this analysis corresponds to the

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[15] Derived from the word 'ecotype' meaning the smallest taxonomic subdivision of an ecospecies, consisting of populations adapted to a particular set of environmental conditions. The populations are infertile with other ecotypes of the same ecospecies.

[16] There is also a caveat with respect to interpreting the significance of a freezing resistance temperature derived experimentally, against actual species response to freezing temperature in the wild. Many plants increase in freezing tolerance upon exposure to low nonfreezing temperatures, a phenomenon known as 'cold acclimation'. For instance, rye, a species which normally has a freezing resistance of -5 ^{o}C, having undergone cold acclimation at low non-freezing temperatures, can survive freezing down to -30 ^{o}C (Thomashow, 1999).

fundamental limits of the distribution range, and not the realised species distribution. At the species' southern range limit in New Zealand, and around the Central Plateau on the North Island, it would be expected that the damaging influence of frost on species distribution and abundance would be more pronounced, especially in exposed areas, or where *Tradescantia* had reduced frost protection. Typical damage to native species compared with expected damage for *Tradescantia* on the basis of frost resistance values is shown in Figure 2.3, which illustrates the frost-sensitivity of this species.

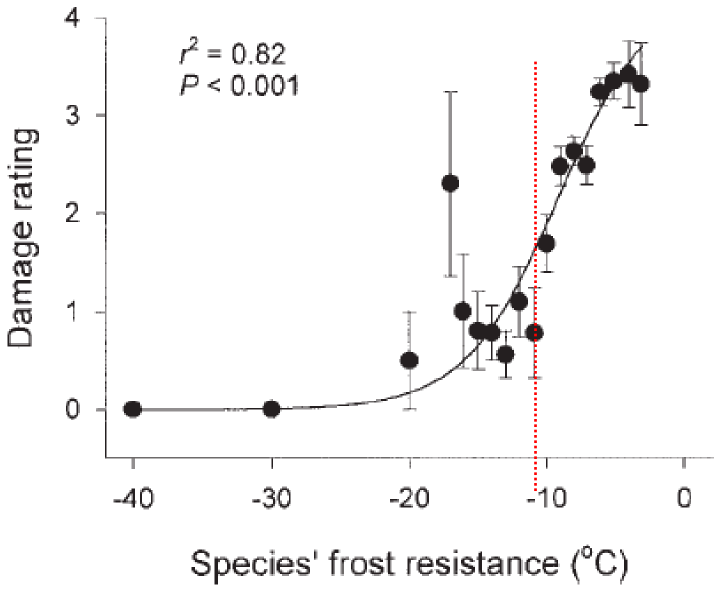

Figure 2.3 Damage incurred from a single extreme event of frost over a two week period with temperatures as low as -15 °C, versus experimentally determined frost resistance measurements. Means of observations are averages of damage over intervals of one degree of frost resistance. The r^2 value indicates the fit of the regression line to the mean values of damage. The red line has been inserted by the author to indicate where *Tradescantia* would lie using the experimentally-derived frost resistance of -4 °C. This line indicates the low frost resistance and high damage rating that would be likely for this species when compared with the other native species. These sorts of extreme frosts are prevalent only in some parts of the country including the Otago Plains on the South Island. (Source: Bannister, 2003a, used with permission).

2.4.1.1.1 Exploratory Analysis

New Zealand occupies a broad latitudinal (35" to 47"s) and climatic range (Wardle, 1991). Figure 2.4 shows the full range of observed values for mean minimum temperature, for the coldest months, July and August, MTminJ-A, at a national scale, based on the LENZ climatology layers. Leathwick (2002) records that the lowest values for MTminJ-A would occur in inter-montane basins, alluvial plains, and/or glacial outwash terraces subject to extreme winter minima, often through temperature inversion[17]. The highest values of MTminJ-A would occur either in montane areas with good cold-air drainage, or in coastal areas exposed to a strong maritime or wind influence (Leathwick, 2001). The MTminJ-A ranged between -7.9 and 10.95 ^{o}C (Figure 2.5) and distribution of *Tradescantia* was observed where MTminJ-A values were between -3 ^{o}C and 8.25 ^{o}C (see Figure 2.6). The lowest observed value at a mountain-top site on Mt Taranaki, New Plymouth, New Zealand, was close to the freezing resistance temperature of -4 ^{o}C. The upper limit of 8.25 ^{o}C indicates that in warmer regions in the far north of the North Island, *Tradescantia* was not observed, i.e. where 8.25 ^{o}C < MTminJ-A < 11 ^{o}C. This may relate more to a lack of sampling in the far north, or that the physical habitat is unsuitable, rather than that the area is climatically unsuitable, given that temperatures there would be expected to be closer to the native range of the species and other sub-tropical locations where it is found (including SE Brazil, Argentina, Florida, Pacific Island sites). Defining the optimal distribution of the species requires a subjective delineation of upper and lower optima of MTminJ-A. These optima appear to fall between 2.65 ^{o}C and 6.75 ^{o}C, in New Zealand; however, these values are likely to reflect association with land cover. In Figure 2.4, the experimentally-derived frost threshold (based on daily data) is shown using a monthly mean temperature spatial layer. While this is a jump in the temporal interval, i.e. from daily to monthly, it is expected that areas with monthly averages of -4 ^{o}C will also be the areas with a higher frequency of daily temperatures at or below -4^{o}C, and consequently will be likely to exclude *Tradescantia* through frost damage. The monthly MTminJ-A was used, because daily data was not available in this spatial dataset.

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[17] A temperature inversion is when the surface temperatures are lower than the air temperatures (Wardle, 1985).

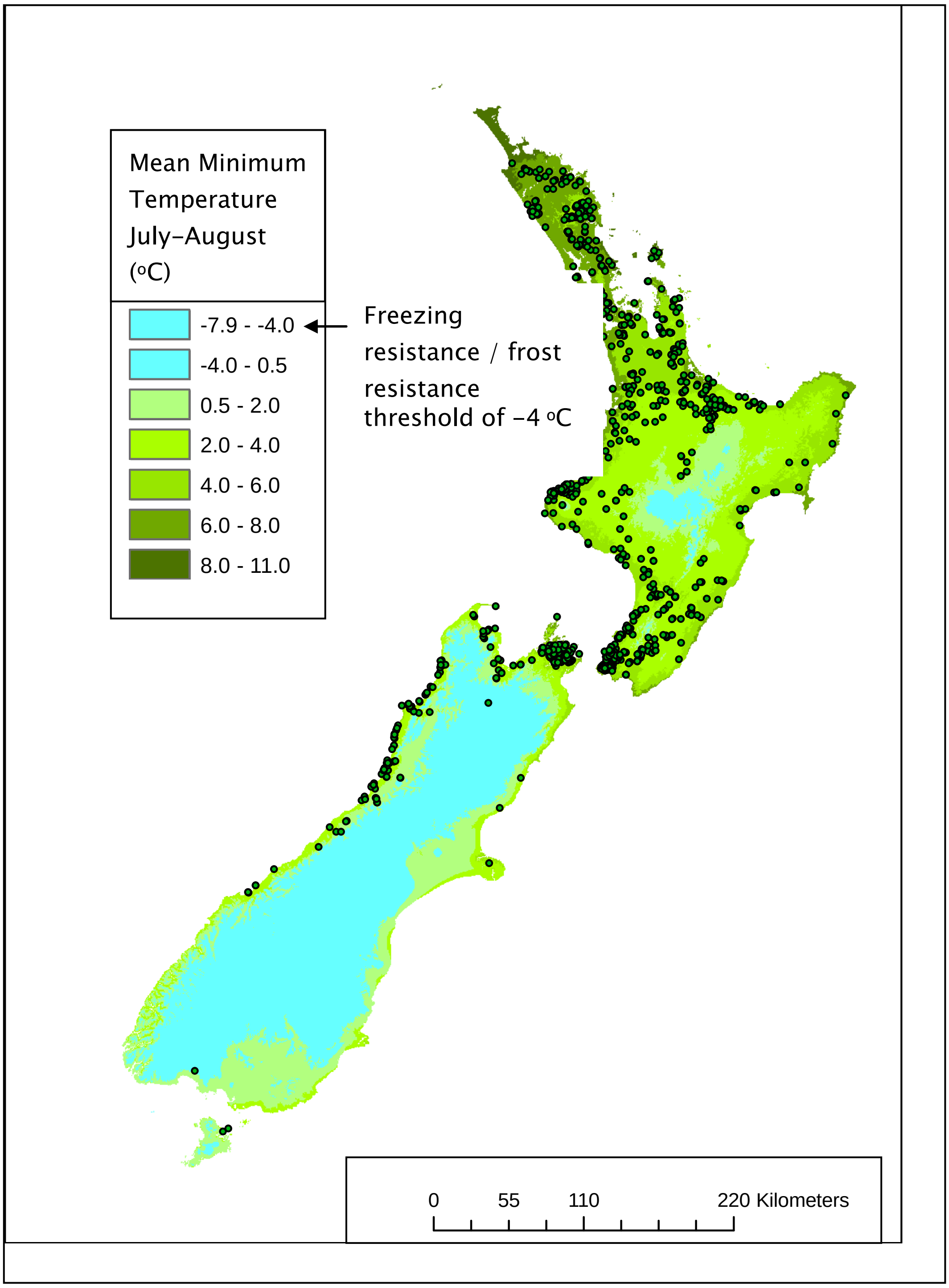

Figure 2.4 The distribution of *Tradescantia* versus mean minimum temperature (July-August), MTminJ-A. Dots represent BioWEB observations of *Tradescantia*[18]. The light blue class delineates the -4 °C frost resistance threshold which for *Tradescantia*, appears to broadly match the species' distribution in New Zealand.

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[18] In all maps used in this section, at the national scale, the dots will represent the national BioWEB observations of *Tradescantia* (used with permission)

The effect of frost resistance threshold on the distribution of *Tradescantia* is clearly evident in the South Island of New Zealand, where the greater latitude leads to lower overall temperatures as well as lower minimum temperatures. In the South Island, particularly on the West Coast, it is likely that the suitable sites located within the -4 °C threshold are unoccupied because of the inaccessibility of sites as a result of steep topography and dense intact indigenous vegetation. Furthermore, most of the West Coast south of the southern-most *Tradescantia* observations has very low human settlement, which would restrict propagule dispersal.

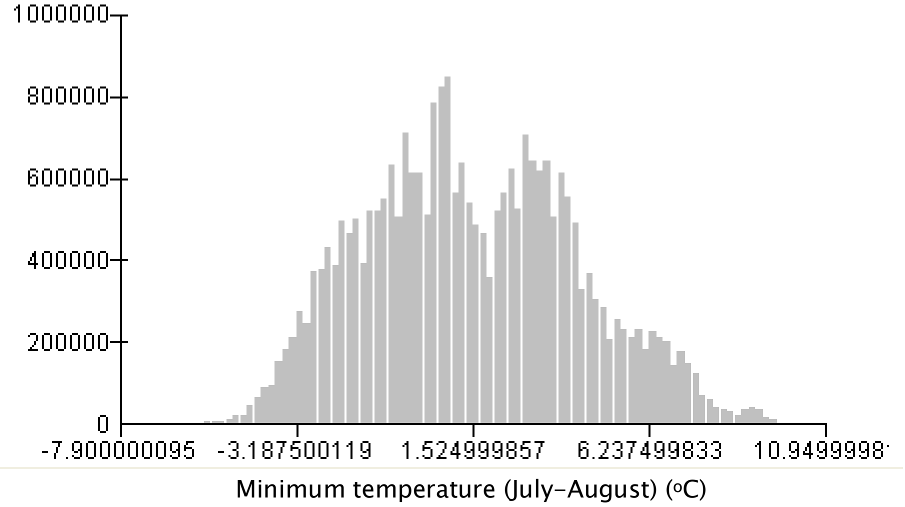

Figure 2.5 National-scale gradient of LENZ mean minimum temperature (July-August) versus the frequency of raster cells. The higher temperatures correspond to lowland and coastal areas, while the lowest temperatures correspond to the Alpine and high altitude mountain ranges of the North and South Islands.

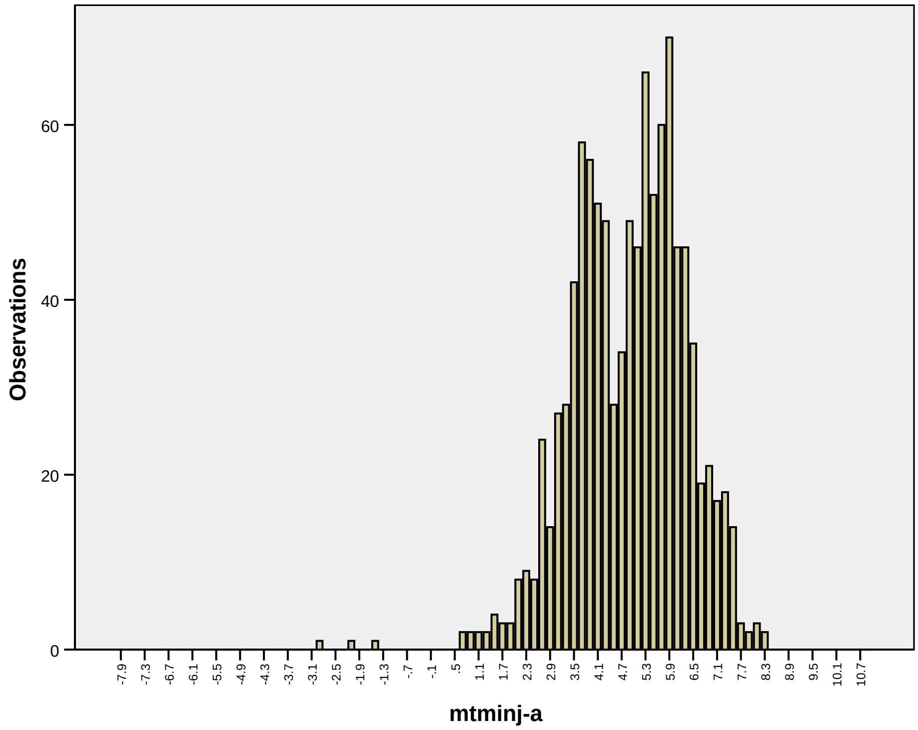

Figure 2.6 Frequency of *Tradescantia* observations versus the national-scale Mean Minimum Temperature (July-August), MTminJ-A. The graph shows that the majority of the observations were located within MTminJ-A range of about 2.0°C-8.0°C, and indicates the species optimum for MTminJ-A.

Table 2.1 provides descriptive statistics which show that the geographic areas covered by each of the temperature intervals also has an effect on the percentage of observations of *Tradescantia* within those intervals, i.e. it was expected that because 41.5% of New Zealand falls in the temperature range 2.0-7.9°C, which is also a more suitable a milder range of temperatures, that more observations would be found there than if there was a very small percentage of New Zealand in this temperature range.

In order to determine if the frequency of observations of Tradescantia was non-random (i.e. had an association with) MTminJ-A, a chi-squared statistic, χ^2*, was calculated, using the method described in Mendenhall and Beaver, 1991, pgs. 494-497. The same procedure was followed for all national level variables (MTminJ-A, Annual Water Deficit, Elevation, Slope, and LCDB2 classes), except Frost Free Period which because of its high correlation with TminJ-A is excluded as a variable for Chapter 3. All results are found in captions of Tables 2.1 – 2.5.*

MTminJ-A range (^{o}C)	**Raster cell count per range**	**% of raster cells**	**Observations of *Tradescantia***	**% observations of *Tradescantia***
-7.9 – -2.9	1179654	4.4	0	0
-3.0 – -0.1	7709310	28.8	3	0.3
0.0 – 1.9	6500620	24.3	16	1.6
2.0 – 7.9	11103658	41.5	1003	97.5
8.0 – 10.7	237246	0.9	7	0.7
Totals:	**26730488**	**100%**	**1029**	**100%**

Table 2.1 Descriptive statistics for the comparison of percent raster cells per MTminJ-A range (based on Figure 2.2) versus the percent of observations of *Tradescantia* within those MTminJ-A ranges. This shows that the majority of the observations (97.5%) were in the MTminJ-A range of 2.0-7.9 ^{o}C, which occupies 41.5% of the geographic area of New Zealand. (Note: Chi-squared statistic, χ^2 = 1332.1; using α=0.05; therefore, I reject the null hypothesis that the number of *Tradescantia* observations is random in each temperature range category if χ^2 >9.48773 (df=k-1=5-1=4); in other words I accept the alternative hypothesis that *Tradescantia* has a non-random distribution with respect to MTminJ-A, and is more prevalent in some MTminJ-A categories).

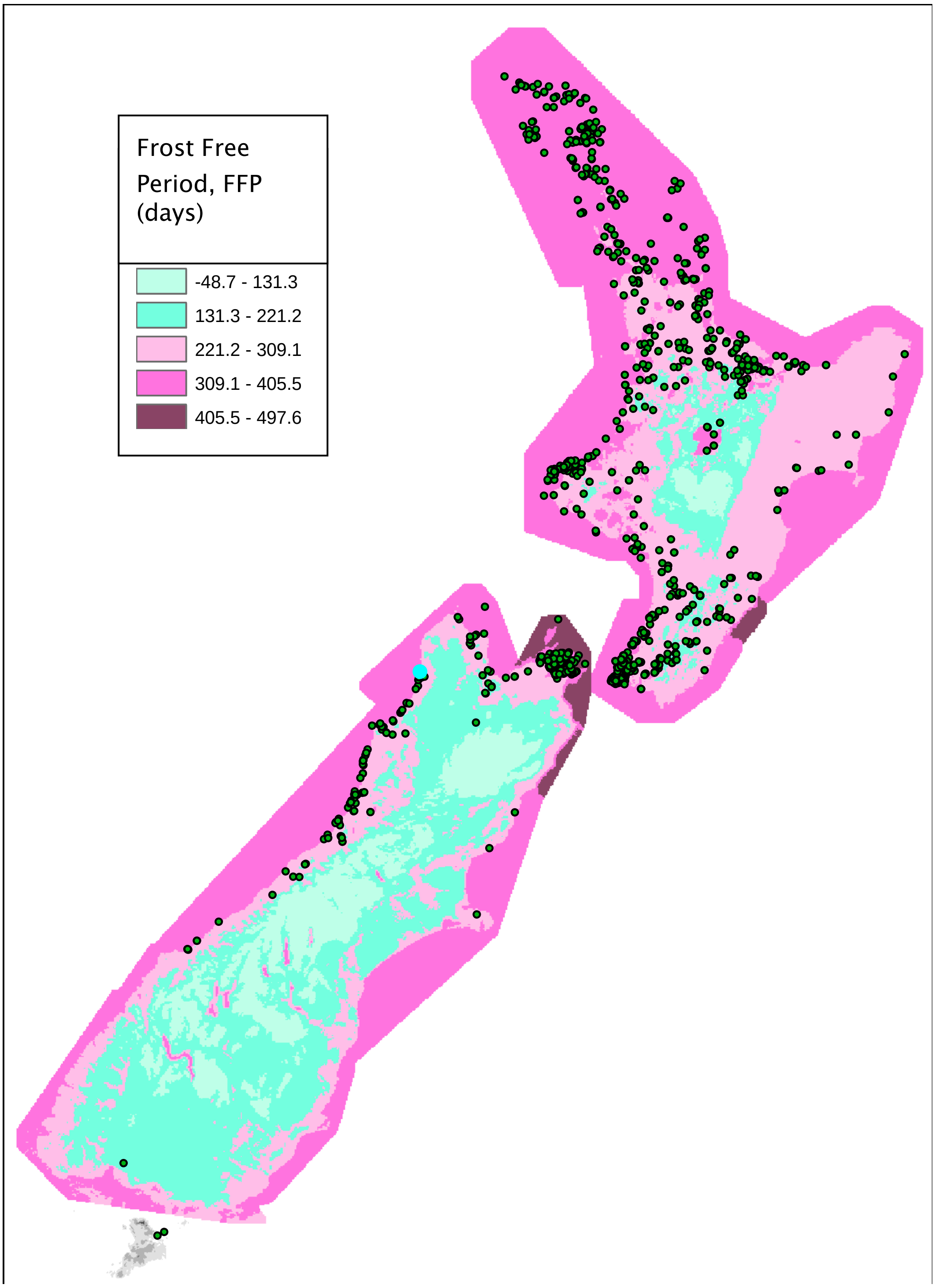

Figure 2.7 Distribution of *Tradescantia* versus Frost Free Period, FFP (days). There is no evidence of *Tradescantia* occupying sites in geographic areas with low frost free period (i.e. higher occurrences of frost) between values of -44 and 200 FFP, except for one observation at the south of the South Island. (The FFP Data was prepared and provided by the National Institute for Water and Atmospheric Sciences, NIWA, Wellington, New Zealand, used with permission).

Figure 2.7 indicates that the species is largely absent from areas where the Frost Free Period, FFP < 200 days. Such areas fall distinctly in the Central Volcanic Plateau on the North Island, along the full extent of the Alpine Central Mountain Ranges and in the eastern Canterbury Plains and Southland Plains of the South Island. The eastern side of the Alpine Ranges is also known to experience cold temperature inversions. Both the literature and observed species distribution suggest that these areas are broadly unsuitable for *Tradescantia* establishment.

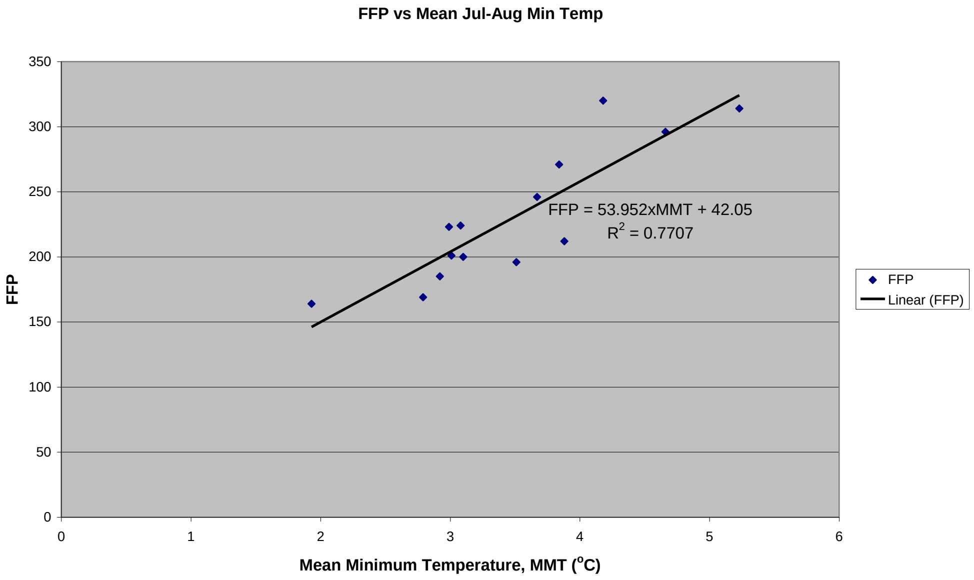

Figure 2.8 Mean minimum temperature versus Frost Free Period (FFP) for a site in Hawkes Bay, New Zealand, (Data source: National Institute for Water and Atmospheric Sciences, NIWA, 2007, provided by Dr. Andrew Tait, NIWA Wellington, used with permission).

Frost Free Period is considered to be positively linearly correlated to Mean Minimum Temperature at a local level as shown by Figure 2.8 for a frost-prone site in the eastern Hawkes Bay region of the North Island, New Zealand (r^2 = 0.7707). This may not be the rule for all geographic areas, however, given the high correlation of the two variables, only one variable will be selected for the species distribution modelling in Chapter 3, and MTminJ-A is selected instead of FFP.

It is concluded that at the national level, the -4 ^{o}C frost resistance threshold broadly delimits climatically suitable areas showing *Tradescantia* presence, from areas that are unsuitable and show almost no presences. Frost Free Period is less definitive than frost resistance threshold, since *Tradescantia* appears to be restricted to areas where the FFP <200 days, which leaves many inland areas unsuitable.

2.4.1.2Precipitation – Annual Water Deficit & Drought

A range of processes affect the relationship between water availability and the distribution of plants. While measures of precipitation *per se* are of limited value for understanding these relationships, other calculated variables, for example the relationship between precipitation and evapotranspiration, are much more relevant. This is because similar amounts of rainfall can produce different effects on plants depending on both its seasonal distribution and rates of evapotranspiration. A further complication for many plants is that rates of evapotranspiration are regulated both by the water supply in the soil around the plant roots and the humidity of the air (Leathwick et al., 2003).

In general, as air becomes drier, the rate at which water evaporates increases. When either the soil or air is very dry, water losses from the leaves of plants may exceed their ability to move water from their roots to their leaves, and they respond by closing their leaf pores or stomata to prevent excessive water loss. Leathwick (1995) found climatic estimates indicating water availability ratio (precipitation to potential evapotranspiration, or R/E), October vapor pressure deficit (VPD) and soil Annual Water Deficit (referred to hereafter as AWD) described plant productivity more effectively, than estimates of precipitation levels per se. These indices have subsequently been used also by (Zaniewsky et al., 2002), particularly in relation to national scale gradients and their spatial correlation to native vegetation distributions. AWD[19] (Leathwick et al., 2003),

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[19] Annual water deficit is the sum of monthly water deficits (which for New Zealand typically

and other related indicators like Potential Evapotranspiration Deficit (PED), can be used as indicators of water stress. PED for example, is used as a drought risk indicator at the national scale in New Zealand (Mullan et al., 2005).

There are some indications that *Tradescantia* is drought-sensitive (Standish et al., 2001), which may limit its biomass accumulation and local abundance or even its ability to establish in an area (for instance, in eastern Wairarapa, Howell et al. 2000a). This warrants an exploration of the distribution of *Tradescantia* to AWD in New Zealand.

Figure 2.9 shows the distribution of *Tradescantia* against AWD in New Zealand. On average most lowland sites in the North Island experience at least some degree of AWD, with the highest deficits occurring in the east about Gisborne and in Hawkes Bay and Wairarapa. Moderate deficits occur in Manawatu and the far north towards Cape Reinga. Lowland South Island sites lying to the east of mountain ranges, and extending from Nelson to Dunedin, generally experience moderate to high annual AWDs, with New Zealand's highest annual AWD occurring in Central Otago. Low to moderate deficits are experienced in Southland, reflecting its greater exposure from the south and southwest (Leathwick et al., 2003).

2.4.1.2.1 Exploratory Analysis

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occur in the months of November through to February). First, solar radiation and temperature are used to calculate average total evaporation in each month, and this is greatest for summer months when solar radiation is greatest. This is then compared to rainfall: where the rainfall is less than the potential evaporation, it produces a monthly water deficit. The monthly water deficits are summed to produce the annual water deficit (Leathwick et al., 2003).

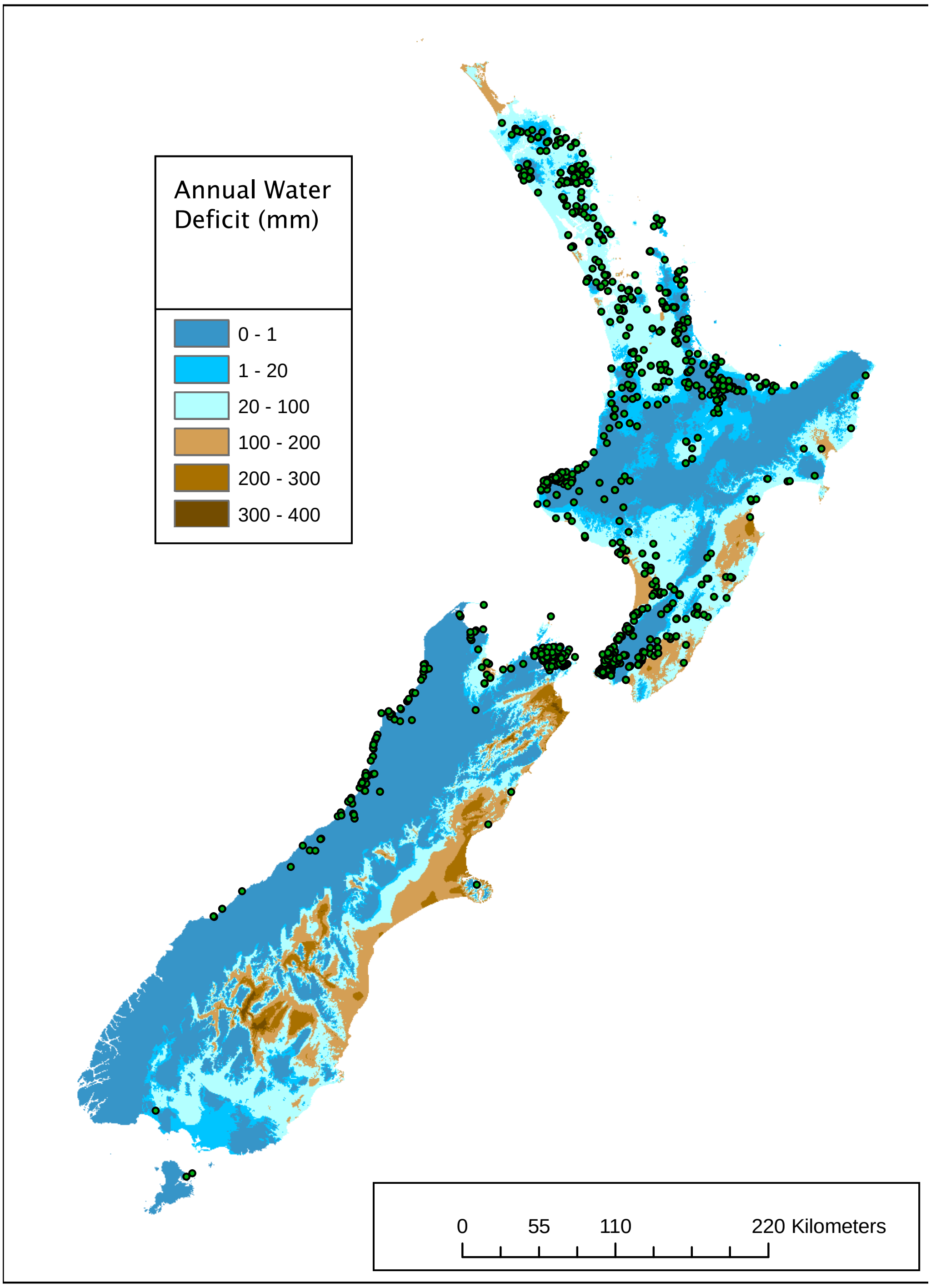

Figure 2.9 Distribution of *Tradescantia* versus Annual Water Deficit (mm) for New Zealand. The driest parts of the country (Gisborne, Hawkes Bay, Marlborough, most of coastal Canterbury, and inland Otago) (Mullan et al., 2005). These areas correspond with low presence of *Tradescantia* particularly where deficit values are ≥ 300.

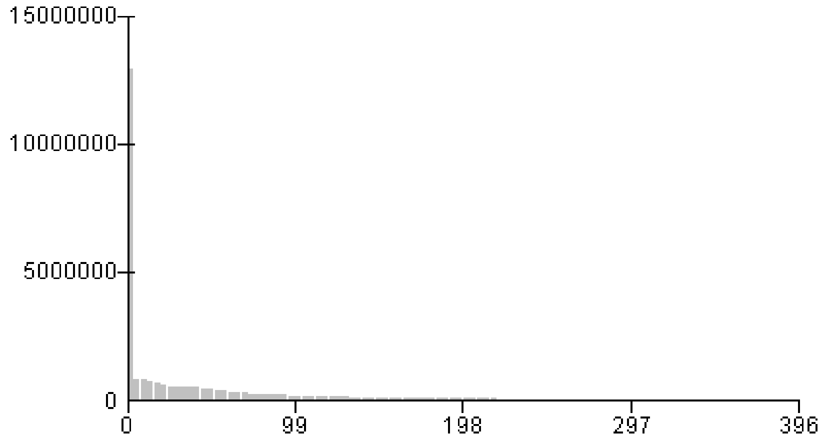

Figure 2.10 National-scale gradient of LENZ Annual Water Deficit (mm) versus the frequency of raster cells. The graph shows that there is a predominance of sites cells with AWD=0mm, and a wide range of AWD values between 1-396mm The higher values corresponding typically to eastern areas of both North and South Island in the rain shadow of the large mountain ranges.

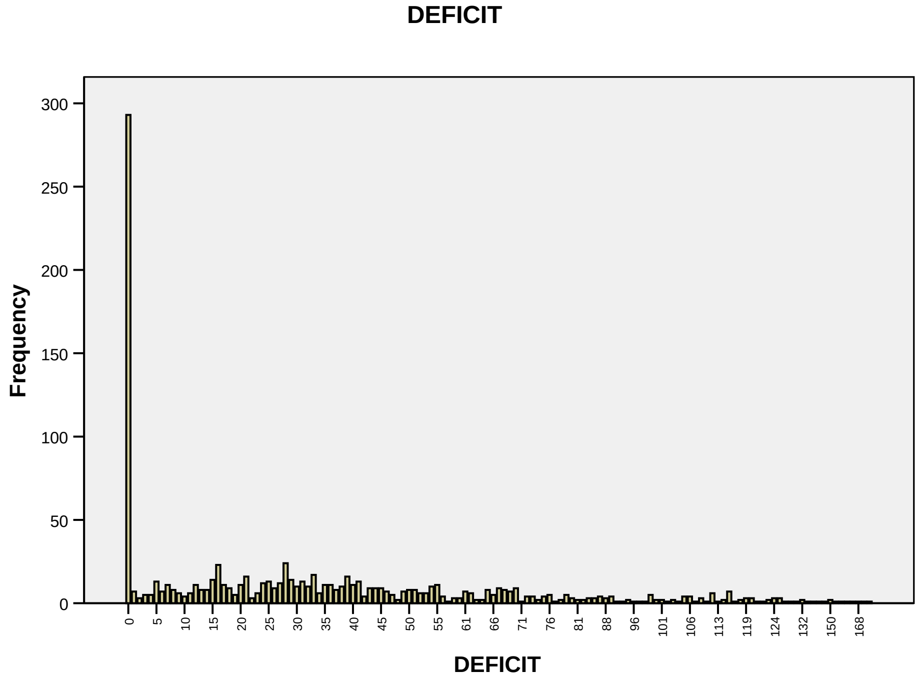

Figure 2.11 Frequency of *Tradescantia* observations versus the national-scale Annual Water Deficit (mm). A prevalence of observations in cells with AWD=0 is evident, with other observations scattered in areas of varying AWD.

AWD range (mm)	Raster cell count per range	% of total no. of cells	Observations of *Tradescantia*	% observations of *Tradescantia*
0	12268627	45.9	293	28.8
1-79	9415931	35.2	616	60.5
80-169	3774231	14.1	109	10.7
170-396	1271699	4.8	1	0.1
Totals:	**26730488**	**100%**	**1019**	**100%**

Table 2.2 Descriptive statistics for the comparison of percent raster cells per annual AWD range (based on Figure 2.8) versus the percent of observations of *Tradescantia* within those AWD ranges. This shows that the majority of the observations (89.3%) were in the AWD range of 0-80 °C, which occupies 81.1% of the geographic area of New Zealand. (Note: Chi-squared statistic =305.2; using α=0.05; therefore, I reject the null hypothesis that the number of *Tradescantia* observations is random in each AWD range category if χ^2>7.81473 (df=k-1=4-1=3); in other words I accept the alternative hypothesis that *Tradescantia* is non-randomly distributed across the AWD range categories and is more prevalent in some AWD categories).

AWD ranges between 0-396mm for New Zealand (Figure 2.10), whereas observations of *Tradescantia* occur on sites within the range of 0-170mm (Figure 2.11). Frequency of presence/prevalence was highest on sites with AWD = 0. However, many observations occurred in areas with AWD between 1 and 170. The observations found in areas with higher values of AWD may be in sheltered sites which afford more moist environments for *Tradescantia*, and may also be related to other local factors which make the areas suitable for this species to establish and grow. Typically, *Tradescantia* was either absent or had very low frequency of presence/prevalence in areas that were known to have the highest AWDs (see Figure 2.9) including parts of Manawatu, Wairarapa, Hawkes Bay, Gisborne, the far north of the North Island, the Canterbury Plains and the Central Otago Plains. However, it is more likely that this is related to the fact that all of these areas have also suffered the largest losses of indigenous biodiversity to agriculture in New Zealand, greatly reducing the number and extent of suitable habitat sites for weeds like *Tradescantia*. Table 2.2 provides descriptive statistics, however, no clear patterns emerge, except that up to 46% of New Zealand has a AWD=0. AWD is selected as an explanatory variable for the species distribution modeling because the lower values are associated with higher frequencies of *Tradescantia* and higher AWD values are associated with absence (although the absence is likely to be an indirect result of the clearing of vegetation in large agricultural plains).

2.4.2 Topography and Distribution

2.4.2.1Elevation

New Zealand has a very diverse topography. Elevation is often used as a surrogate or indirect driver of native vegetation patterns. Climatic variables, particularly minimum temperature, are typically correlated with elevation, however, because minimum temperature is often location-specific, using elevation as its surrogate is often not suitable in assessing species distribution (Leathwick, 1995). Nevertheless, elevation is an important variable in the context of invasive species because many invasive species are known to be more prevalent in lowland areas. *Tradescantia* is a prime example of a weed that benefits from this pattern (Timmins and McKenzie, 1995). Other examples of environmental weeds that are prevalent in coastal and lowland areas include *Ageratina riparia* (mistflower), *Ageratina adenophora* (mexican devil), *Alternanthera philoxeroides* (alligator weed), *Araujia sericifera* (moth plant), *Asparagus scandens* (climbing asparagus), and *Clematis vitalba* (old man’s beard) amongst numerous others.

2.4.2.1.1 Exploratory Analysis

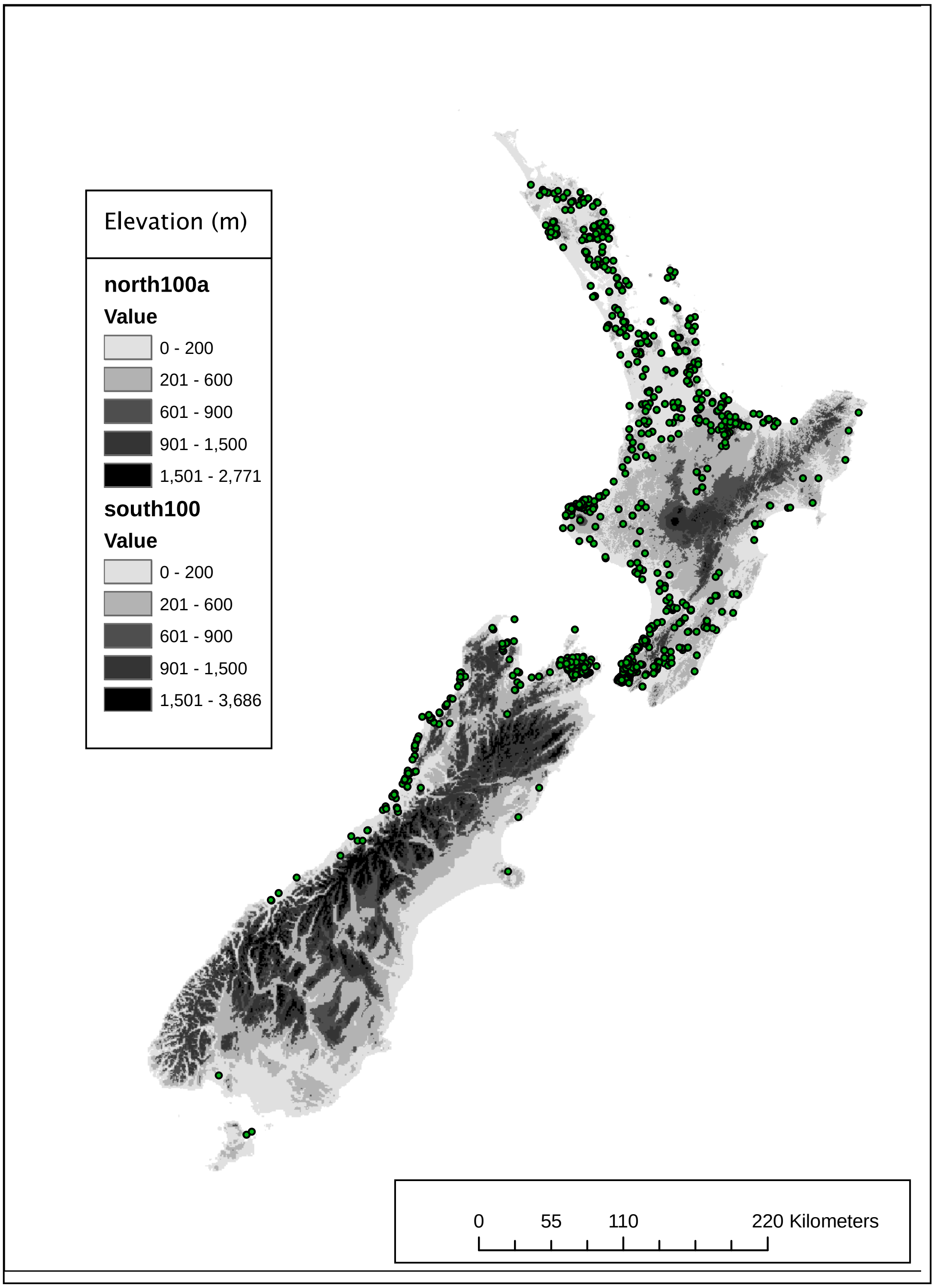

Figure 2.12 Distribution of *Tradescantia* versus elevation (m) for New Zealand versus the distribution of *Tradescantia*. (Note: north100a refers to the North Island dataset at 100m and south100 to the South Island dataset at 100m).

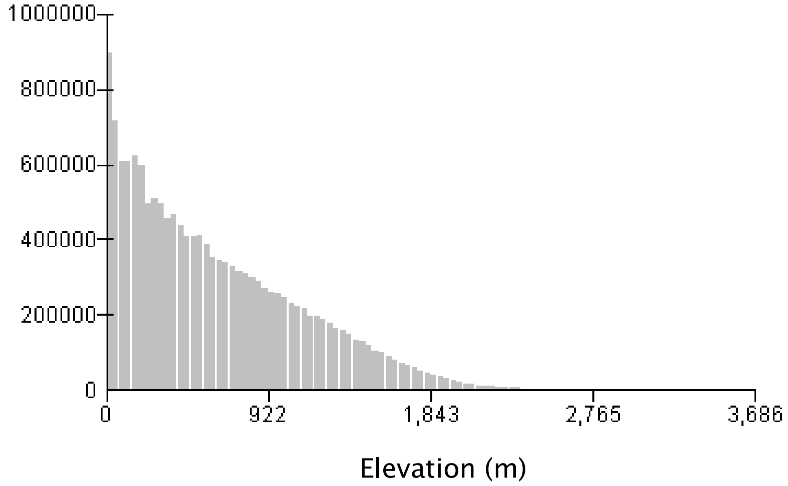

Figure 2.13 National-scale gradient of elevation (m) in New Zealand versus the frequency of raster cells per elevation value. The national topography is very varied, and therefore, its influence on climate and vegetation is marked in New Zealand.

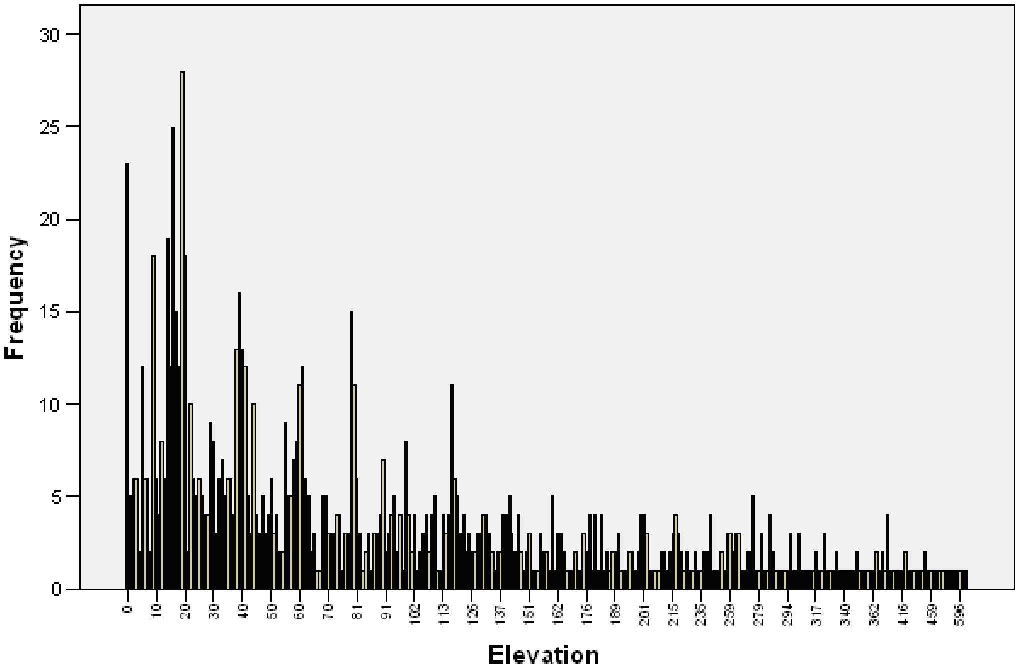

Figure 2.14 Elevation (m) versus the frequency of *Tradescantia* observations found per elevation. It shows a prevalence of *Tradescantia* in lower elevation sites, through to medium and low prevalence at mid to higher elevations.

Elevation range (m)	Raster cell count per range	% of total no. of cells	Observations of *Tradescantia*	% observations of *Tradescantia*
0-119	5980488	22.4	284	27.4
120-600	12459579	46.6	749	72.2
600-3686	8287166	31.0	4	0.4
Totals:	26727233	100%	1037	100%

Table 2.3 Descriptive statistics for the comparison of percent raster cells per Elevation range (based on Figure 2.12) versus the percent of observations of *Tradescantia* within those elevation ranges. This shows that the majority of the observations (99.6%) were in the Elevational range of 0-600m.a.s.l., which occupies 69% of the geographic area of New Zealand. (Note: Chi-squared statistic, χ^2 = 471.2; using α=0.05; therefore, I reject the null hypothesis that the *Tradescantia* observations are randomly distributed in each elevation range category if χ^2 >5.99147, (df=k-1=3-1=2); in other words I accept the alternative hypothesis that *Tradescantia* is non-randomly distributed across the range categories and is more prevalent in some elevation categories).

Elevation ranges between and 0 and about 3686 m.a.s.l. in New Zealand (Figures 2.12 and 2.13). Figure 2.14 shows that *Tradescantia* is typically prevalent below 120m.a.s.l. The presence observations above this elevation are associated with native vegetation and other protected areas typically in upland rural dwellings. Table 2.3 provides descriptive statistics which show interestingly that the majority if the observations were found, between elevations 0-600m.

2.4.2.2 Slope

Except for the very steepest sites, slope mostly affects plants indirectly via its effects on soils and microclimate (Leathwick et al., 2002; Reitsma, 1994). Steep sites may be more drought-prone because water drains away to lower sites. Slope is also closely related to the weathering of soils, substrate stability (Leathwick,

2001) and drainage patterns. The other significance of slope is its effect on temperature. This is most marked at night, when a cold layer of air often develops above the earth's surface as it loses heat accumulated during the day. Because this cold air is heavier than warm air, it sinks towards lower parts of the landscape, sometimes producing cold (katabatic) winds that blow from high to low elevations during the night (Barna and Gimson, 2002; Leathwick, 2002). As a consequence of this movement, sites in valley bottoms generally have lower minimum temperatures than nearby sites on ridges and may create what is commonly known as 'frost flats' with a higher localised frost frequency than surrounding areas. The most extensive areas of flat to gently undulating land occur at low elevations in Southland, Canterbury, Manawatu, Wairarapa, and Waikato. Smaller areas of flat to undulating land occur throughout the rest of the country, mostly on alluvial terraces, often forming narrow fingers along valleys floors. Undulating land is most extensive in the North Island, particularly in Taranaki and in southeastern parts of the South Island, while rolling land is most common around Gisborne and in Taranaki and Wairarapa. Hilly land occurs extensively in the foothills of the axial mountain ranges of both islands, in inland Taranaki and in the Urewera and Raukumara Ranges. Steep land is most extensive in the mountains of the South Island, with a smaller area in the axial ranges of the North Island. Very steep land is most extensive in Fiordland on the South Island (Leathwick et al, 2003; Wardle et al., 1973). At the landscape-level slope is useful to identify the riparian gullies that were observed to harbour *Tradescantia* populations on many occasions, particularly in urban areas. In this context, higher slope areas are those likely to be less accessible for vegetation management and more likely to be over-the-fence-dumping sites for urban garden greenwaste. They are typically shady, damp places ideal for *Tradescantia's* growth. Slope is also indicative of steep gully formations and escarpments, which at the landscape level, provide inaccessible and often abandoned or neglected sites where *Tradescantia*, once established after propagule entry, can invade successfully and persist indefinitely in the absence of further disturbance (although if riparian, disturbances are liekly) (references linked to gullies and riparian slopes: Ducros and Joyce, 2003; Malanson, 1993; and Rosgen, 1994).

2.4.2.2.1 Exploratory Analysis

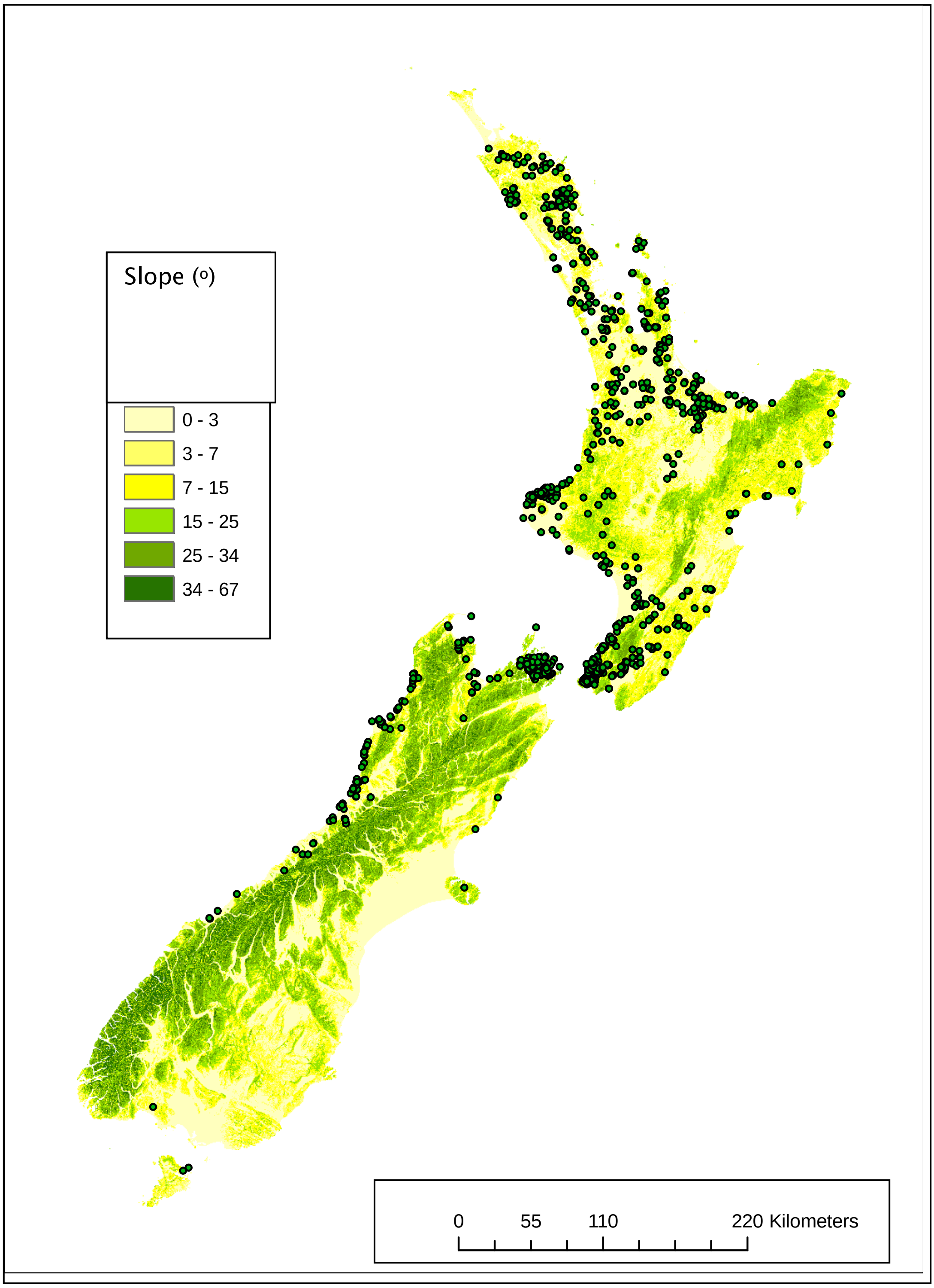

Figure 2.15 Distribution of *Tradescantia* versus national-scale slope classes (in degrees). There is a distinct absence of the species from geographic areas where slope is between 25°-67°, i.e. in the steepest 'montane to mountain' type terrain gradient, and less accessed by humans.

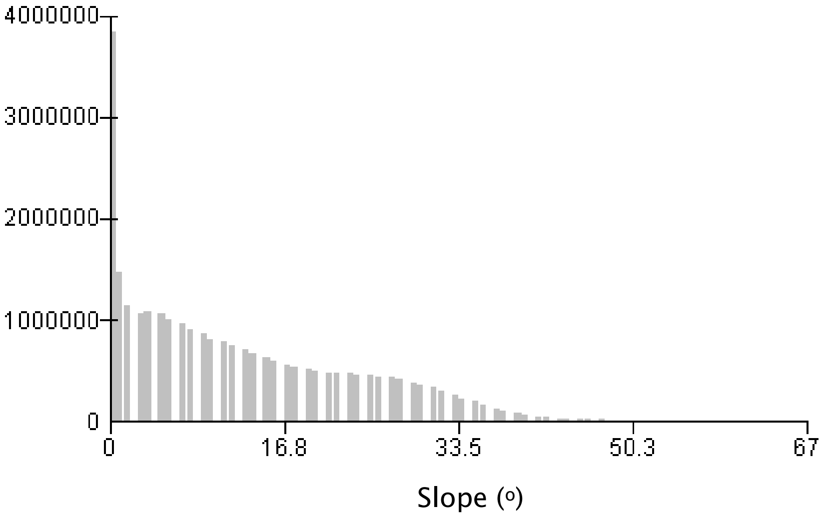

Figure 2.16 National-scale gradient of slope (degrees) versus the frequency of raster cells per slope value. The varied slope indicates an undulating topography with a prevalence of flat and gently sloping areas and the remaining in the higher slope classes with steep land (mountainous regions).

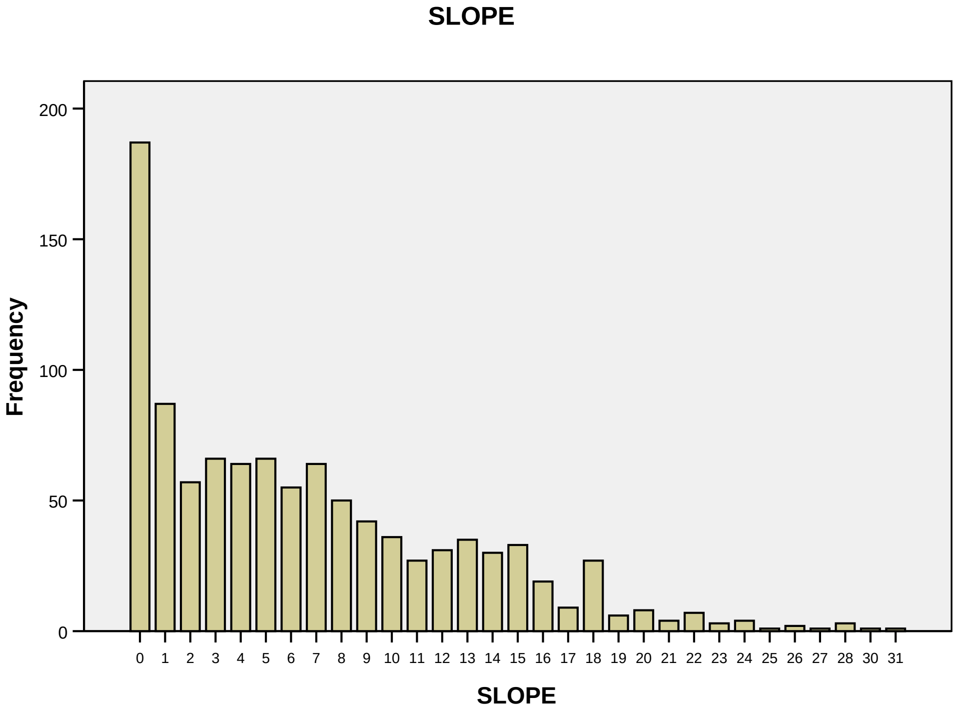

Figure 2.17 Slope (degrees) versus frequency of *Tradescantia* observations, indicating that *Tradescantia* found on relatively flat or low to medium slope.

Slope range (degrees)	Raster cell count per range	% of total no. of cells	Observations of *Tradescantia*	% observations of *Tradescantia*
0-3	7506978	28.1	397	38.7
4-7	4103232	15.4	249	24.3
8-15	6078314	22.7	284	27.7
16-25	4978755	18.6	88	8.6
26-34	3132699	11.7	8	0.8
34-67	930510	3.5	0	0
Totals:	**26730488**	**100%**	**1026**	**100%**

Table 2.4 Descriptive statistics for the comparison of percent raster cells per slope range (based on Figure 2.6) versus the percent of observations of *Tradescantia* within those Slope ranges. This shows that the majority of the observations (90.7%) were in the Slope range of 0-15 degrees, which occupies 66.2% of the geographic area of New Zealand, i.e. there is a high possibility of *Tradescantia* observations falling within these lowland to midland areas within gentle to medium slopes. (Note: Chi-squared statistic, χ^2 = 300.5; using α=0.05; therefore, I reject the null hypothesis that the *Tradescantia* observations are randomly distributed in each slope range category if χ^2 >11.0705, (df=k-1=6-1=5); in other words I accept the alternative hypothesis that *Tradescantia* non-randomly distributed in the slope categories and is more prevalent in some slope categories).

Slope ranges between 0-67 degrees in New Zealand (Figure 2.15 and 2.16) and between 0 and 31 degrees at sites where *Tradescantia* was optimally located (Figure 2.17, Table 2.4). Figure 2.15 suggests that at the national scale, *Tradescantia* is most prevalent on flat land (LENZ slope class=0), and also prevalent in areas with flat to gently undulating land (classes 0-3), undulating (classes 3-7), and rolling land (7-15) (Leathwick, 2003). In these areas it would also be expected that human settlement in urban areas and peri-urban to rural dwellings would be highest, along with most land clearing, forest fragmentation, creation of disturbed edge habitats and access to riparian habitats. In upland areas, riparian habitats are more inaccessible because of surrounding intact native vegetation, or plantation forests in some localities). The only two areas with slope classes 0-3 which show very low prevalence or complete absence are the Canterbury Plains and Central Otago on the South Island. There are two reasons suggested for this:

1) the Plains have been extensively modified for agriculture resulting in 0-10% of indigenous vegetation remaining in both areas (see Figure 2.18);
2) coupled with this, the Plains are also subject to some of the lowest levels of frost free days in the country, on the eastern side of the axial mountains; and
3) Department of Conservation reports that there is a paucity of data collected for *Tradescantia* in the Christchurch area (personal communication Susan Timmins and Clayson Howell, DoC, 2007).

Since the distribution of *Tradescantia* does not appear to be affected directly by slope, it was not selected as an explanatory variable at the national scale.

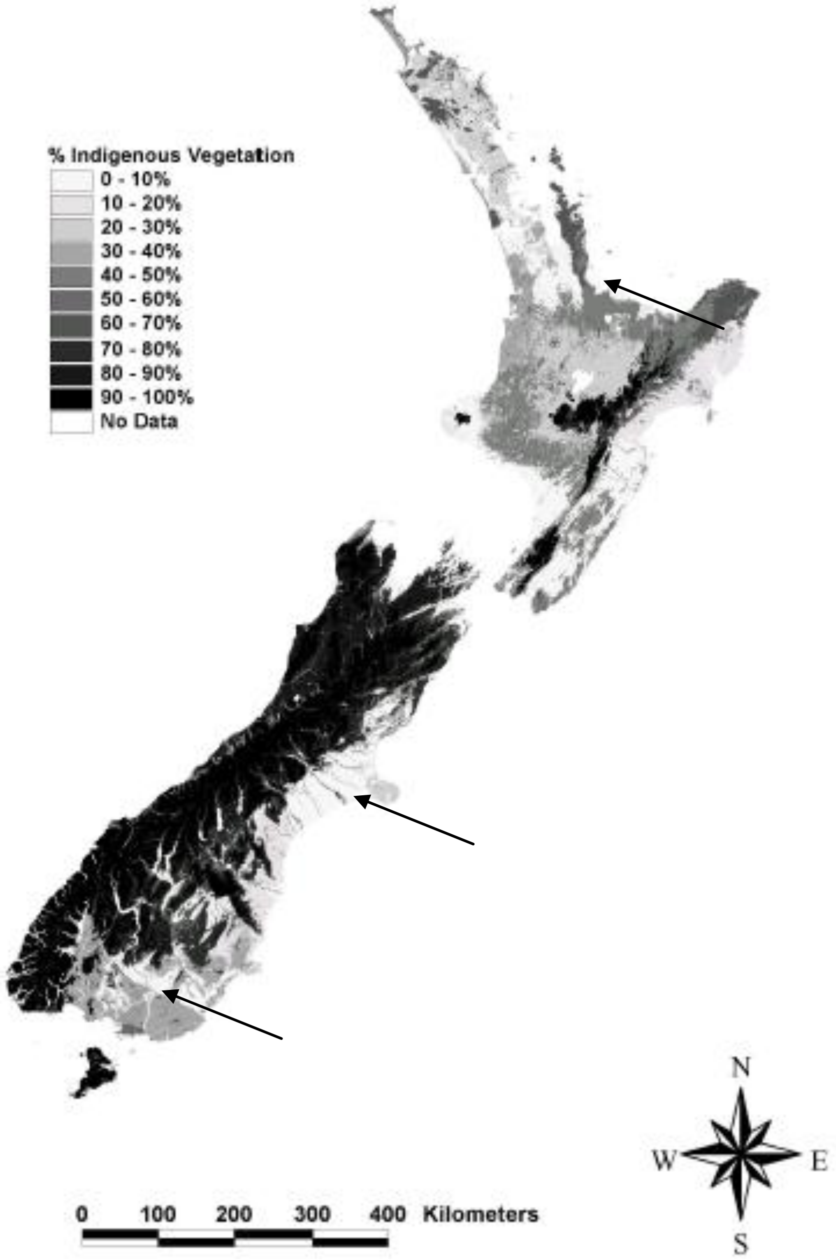

Figure 2.18 Percentage of indigenous vegetation remaining as land cover across New Zealand. Arrows show (1) Western Bay of Plenty (case study area), top (2) Canterbury Plains, middle, and (3) Central Otago Plains, bottom. (Source: Rutledge et al., 2004, pg. 22, used with permission).

2.4.3 Land Use/Land Cover and Distribution

While climate limits plant distribution at a global to national scale, at regional and landscape scales, it is land cover and land use that exert the dominant effects on invasive plant distributions. The need to integrate land use/land cover in the analysis of *Tradescantia's* distribution means that various concepts related to invasion and invasibility must be integrated to address the influence of landscape spatial pattern on invasibility and subsequent invasion by *Tradescantia*. This will be discussed further in Section 2.5 also.

At the most basic level, land cover relates to the various heterogeneous environmental types available as habitat (either suitable or unsuitable) for establishment and invasion by *Tradescantia*. To assess the invasibility of an area, it is necessary to understand the role of elevation, land use, and the spatial arrangement of land use (landscape context) in patterns of distribution of alien species (D'Antonio et al., 2001), in addition to climate. Elevation is an important indicator of microclimatic variation, which may physiologically constrain alien plant invasion (Forcella & Harvey 1983; Wilson et al., 1992). Areas with high human-induced modification of the landscape, such as agriculture/horticulture, exotic forestry and urban landscapes, serve as sources for invasions into more pristine environments (Tyser & Worley 1992; Hobbs 2000; Parendes & Jones 2000). Size, edge:core area ratios and proximity have all been linked with measures of invasibility and will be dealt with in further detail in Section 2.5.1 as a part of the landscape-level assessment. At this stage, land cover and land use are assessed at a national scale to assess the major land cover class types in which *Tradescantia* is distributed, based on the distribution data available.

2.4.3.1Exploratory Analysis

Figures 2.19 and 2.20 show the distribution of *Tradescantia* in relation to the various land cover classes for the North and South Islands respectively.

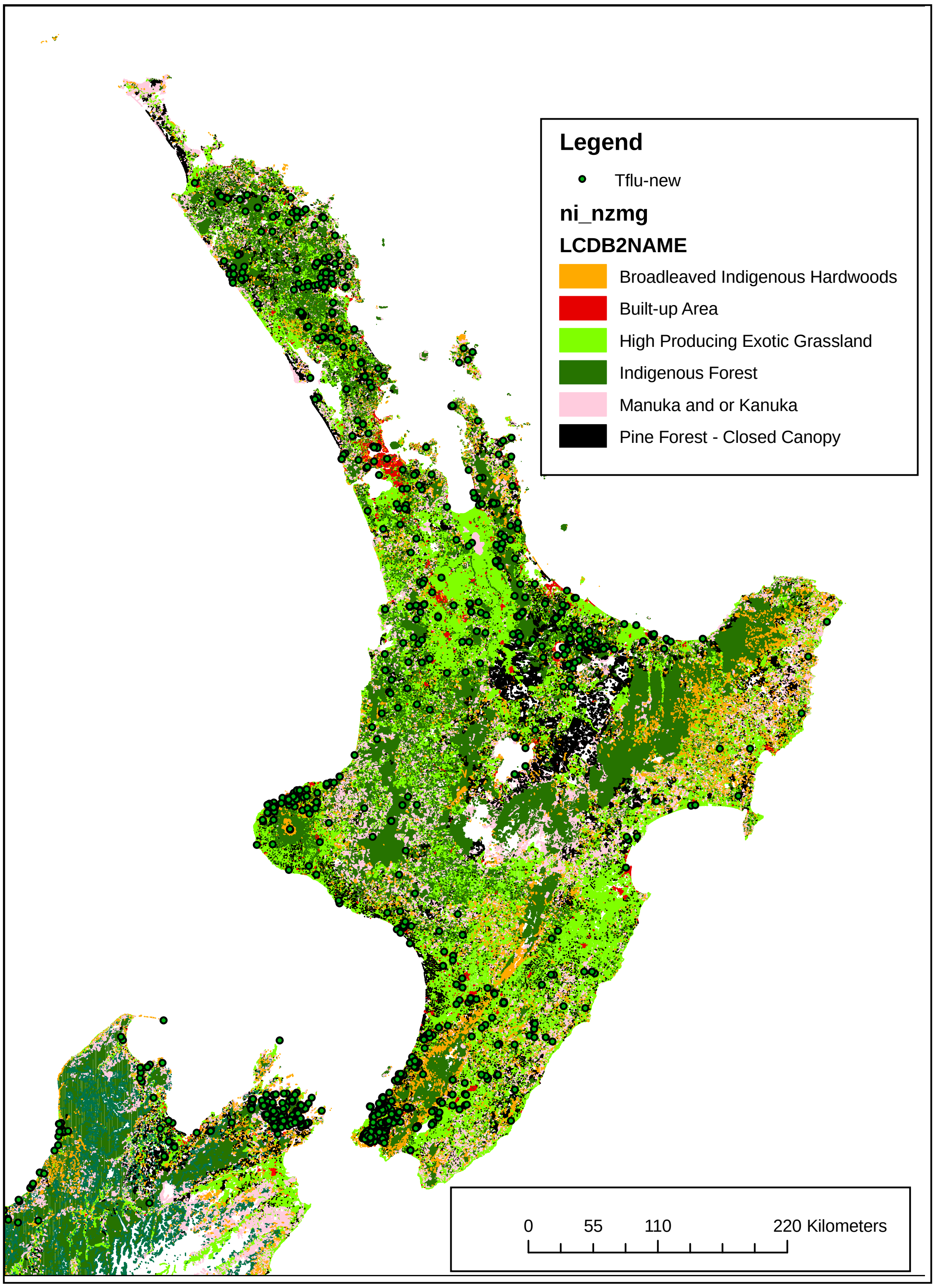

Figure 2.19 Land Cover Database (LCDB) II Classes for the North Island of New Zealand with the observations of *Tradescantia*.

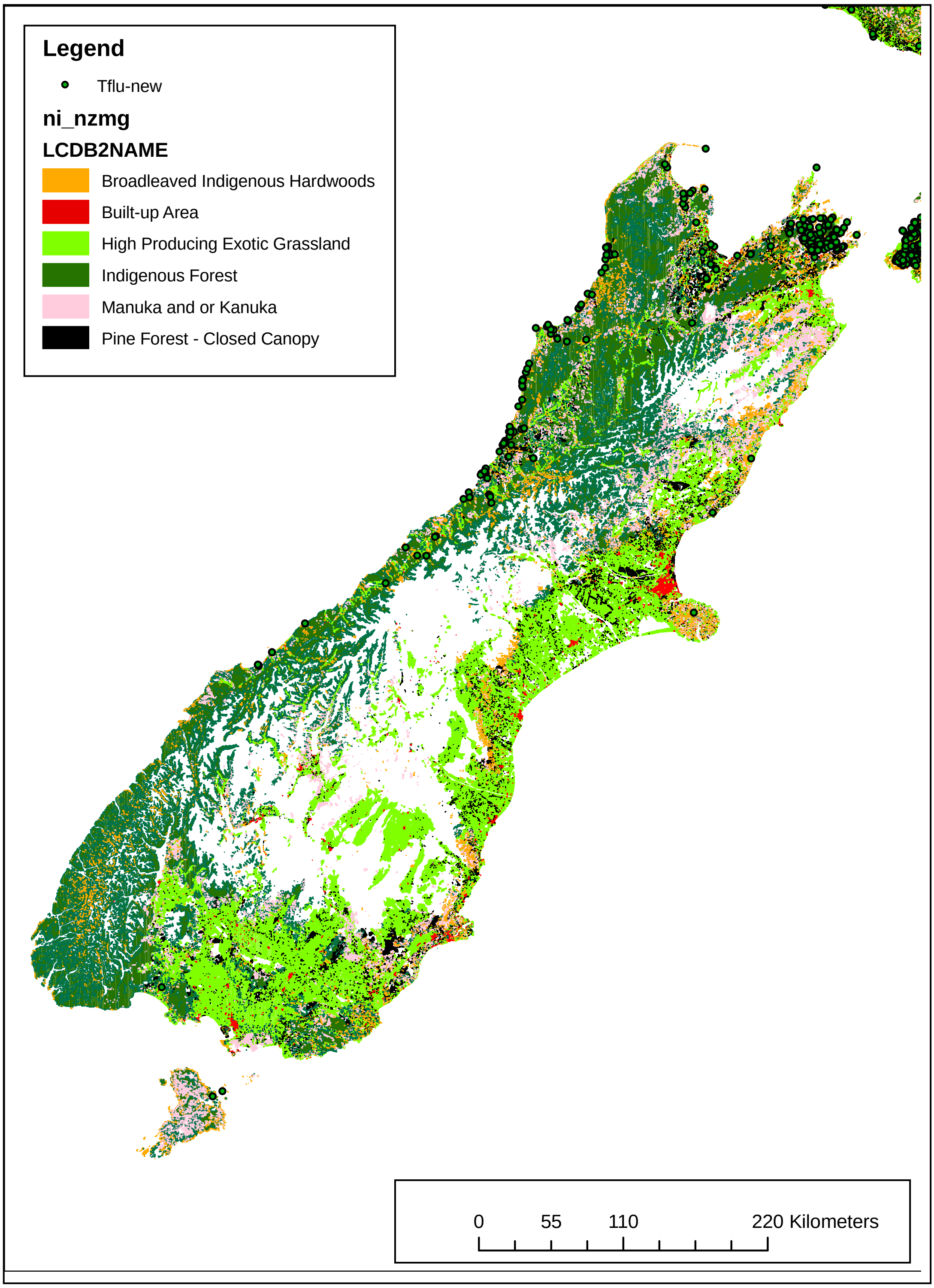

Figure 2.20 Land Cover Database (LCDB) II classes for the South Island of New Zealand and the observations of *Tradescantia*. (Note: the same legend as for Figure 2.19, applies for Figure 2.20).

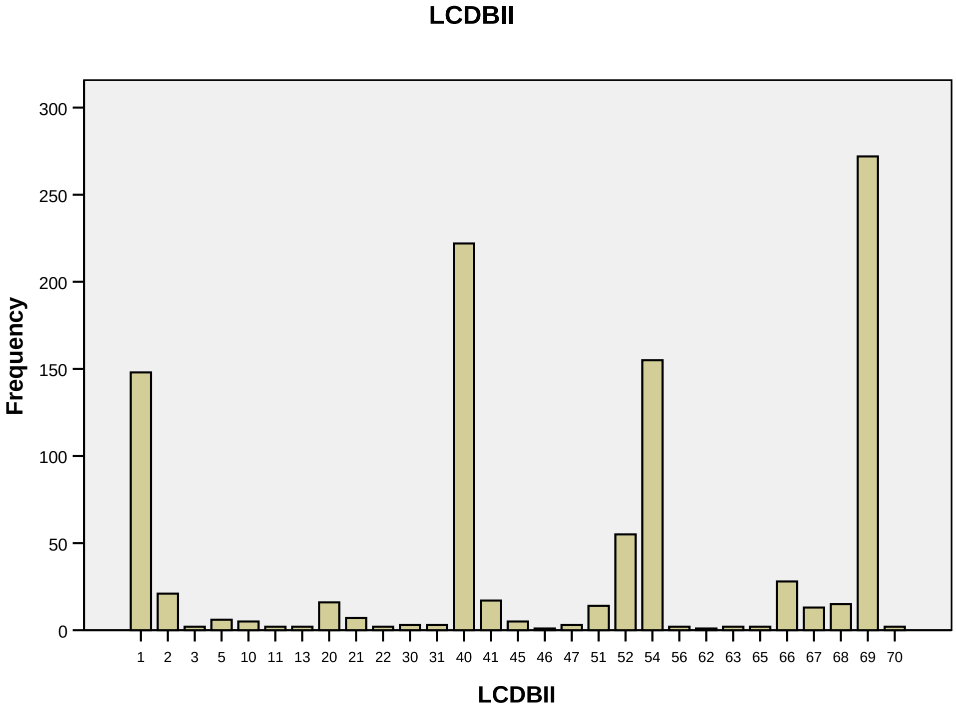

Figure 2.21 National-scale Land Cover Database (LCDB) II classes versus the frequency of *Tradescantia* per class. There is a distinct prevalence of *Tradescantia* in classes 69 (Indigenous Forest), 40 (High Producing Exotic Pasture), 54 (Broadleaved- Indigenous Hardwoods) and 1 (Urban), and to a lesser extent in 52 (Manuka and Kanuka) scrub. It is evident from this graph that *Tradescantia* can occupy a wide range of habitats, though typically requiring that each of the habitats provides, shady, moist disturbed sites for its establishment, growth and survival.

LCDB II Class	**Total Area of LCDB Class**	**% of Total NZ Area**	**No. of Obs. of *Tradescantia***	**% Obs. of *Tradescantia***
1-Built-up Area	163437.6	0.6	148	14.4
2-Urban Parkland/Open Space	40163.8	0.1	21	2.0
3-Surface Mine	9773.4	0.0	2	0.2
5-Transport Infrastructure	6519.2	0.0	6	0.6
10-Coastal Sand and Gravel	51249.4	0.2	5	0.5
11-River and Lakeshore Gravel and Rock	179736.5	0.7	2	0.2
13-Alpine Gravel and Rock	698145.1	2.6	2	0.2
20-Lake and Pond	357525.9	1.3	16	1.6
21-River	81935.7	0.3	7	0.7
22-Estuarine Open Water	92498.8	0.3	2	0.2
30-Short-rotation Cropland	333712.9	1.2	3	0.3
31-Vineyard	25400.4	0.1	3	0.3
40-High Producing Exotic Grassland	8890580.8	33.1	222	21.6
41-Low Producing Grassland	1652286.2	6.2	17	1.7
45-Herbaceous Freshwater Vegetation	88674.1	0.3	5	0.5
46-Herbaceous Saline Vegetation	19215.8	0.1	1	0.1
47-Flaxland	6449.7	0.0	3	0.3
51-Gorse and or Broom	203089.5	0.8	14	1.4
52-Manuka and or Kanuka	1186103.2	4.4	55	5.4
54-Broadleaved Indigenous Hardwoods	539554.6	2.0	155	15.1
56-Mixed Exotic Shrubland	63238.4	0.2	2	0.2
62-Afforestation (not imaged)	49501.8	0.2	1	0.1
63-Afforestation (imaged, post LCDB 1)	85075.9	0.3	2	0.2

65-Pine Forest - Open Canopy	482766.0	1.8	2	0.2
66-Pine Forest - Closed Canopy	977401.14	3.6	28	2.7
67-Other Exotic Forest	132338.4	0.5	13	1.3
68-Deciduous Hardwoods	84191.5	0.3	15	1.5
69-Indigenous Forest	6456940.0	24.1	272	26.5
70-Mangrove	26032.91	0.1	2	0.2
Totals:	**26821558.5**	**100%**	**1026**	**100%**

Table 2.5 Descriptive statistics for the comparison of the percentage of raster cells per LCDBII Class (based on Figures 2.18 and 2.19) versus the percentage of observations of *Tradescantia* within those LCDBII classes. (Note: Chi-squared statistic, χ^2 = 4747.8; using α=0.05; therefore, I reject the null hypothesis that the number of *Tradescantia* observations is randomly distributed in each LCDBII class if χ^2 >41.3372, (df=k-1=30-1=29); in other words I accept the alternative hypothesis that *Tradescantia* non-randomly distributed within the LCDBII classes and is more prevalent in some LCDBII classes).

Figures 2.19, 2,20 and 2.21 above, show that *Tradescantia* is most prevalent in the Indigenous Forest Class (69), High Producing Exotic Pasture Class (40), Broadleaved Indigenous Hardwoods Class (54), Urban Class (1), and Manuka and or Kanuka scrub Class (52). These classes correspond well with habitats that would offer *Tradescantia* shady, moist and damp safe sites for invasion and would offer some frost protection as ‘nurse plants’, while the urban class would provide the main propagule source populations[20]. Given that *Tradescantia* would mostly invade the disturbed edges of these areas, it would provide higher light and nitrogen levels that are suited to *Tradescantia’s* growth (Maule et al., 1995). Table 2.5 provides descriptive statistics of the percentage area covered by each LCDBII class and the percentage of *Tradescantia* observations per class as a

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[20] Note: given the widespread and high prevalence of *Tradescantia* in urban areas (personal observation) it was expected that there would be an even higher frequency of presence observations in the Urban Class than was observed from the species distribution data, and a suggestion is that only few of the many possible occurrences were mapped (as relatively few DoC related sites of interest for sampling were likely to be present in urban areas).

comparison of the proportion of raster cells (geographic area) covered by each class versus the number of observations.

Tradescantia does not exhibit any known species-specific competitive interactions with any native New Zealand species. Therefore, provided with niche opportunities at disturbed edges of these habitats (or within degraded stand of forest or early successional bush) *Tradescantia* is likely to invade successfully. The Kanuka and or Manuka Class (52) typically would be related to either early successional regenerating bush in New Zealand or else bush that has been depleted of its older canopy trees. In both cases light levels within these areas are likely to be higher than in closed/intact forest and therefore preferred for establishment by *Tradescantia*.

The high prevalence of *Tradescantia* in the High Producing Exotic Pasture Class (40) requires further discussion, as this was not an expected result. *Tradescantia* would not be expected to invade sites that were under active management for agriculture (i.e. the actual paddocks) as this would require *Tradescantia* to grow in fully exposed conditions and to be exposed to frost damage in some areas. Moreover, because high producing pasture areas are subject to disturbances from pasture mowing and cattle (which find *Tradescantia* highly palatable species), it is not likely that exposed populations would persist. Instead, in these sites, it is likely that *Tradescantia* is invading small bush remnants and riparian strips associated with farm waterways and streams that intersect with properties, or that the sites represent rural areas where *Tradescantia* is growing around farmhouses or in the vicinity of other farm property buildings. At the resolution of the LCDBII, this small scale remnant vegetation was not likely to be visible. As a result, it was decided that, at the landscape scale, a new dataset would be used that classified vegetation at 15m resolution, based on a riparian landscape classification scheme developed by Landcare Research, New Zealand, using primary ECOSAT satellite imagery. This new dataset would allow an analysis of whether at this new scale, the *Tradescantia* observations in the High Producing

Pasture Class (40) would be re-classed into other riparian vegetation classes. Where there was a re-classification of the observations it would demonstrate a mismatch of habitat that was directly related to the scale of the data used. This has important implications for management of the species at the landscape-scale, with a greater focus on riparian systems, which does not come out strongly from the LCDBII data set alone.

At the scale of the LCDBII, a few other classes are also of interest in providing suitable habitat for *Tradescantia* - the Pine Forest – Closed Canopy Class (66), Other Exotic Forest Class (67) and Deciduous Hardwoods (68); the River and Lakeshore Gravel and Rock Class (11), Lake and Pond (20), River, Open Estuarine Water Class (22). The exotic forest classes, though showing very low prevalence of *Tradescantia*, were suitable because they also provide shady, moist, disturbed safe sites, though to a lesser extent than other forest classes. The water-related classes confer with *Tradescantia* being an invader of moist sites. Another point related to this, is that many of the national scale observations of *Tradescantia*, in the Indigenous forest, Broad-leaved forest and Pine forest classes, are likely to be associated with riparian areas, given that the stream network interlaces its way through these forests as well, within various catchments, and was also indicated by the attribute descriptions for the *Tradescantia* observations.

The chi-squared statistic, χ^2, results with Tables 2.1-2.5, provide evidence that *Tradescantia* is strongly non-randomly associated with all of the variables that were tested, in other words there is a strong association with the distribution of *Tradecantia*, and this therefore justifies the selection of these variables explored in developing the species distribution models. However, FFP, slope, elevation and LCDBII are not used in the species distribution modelling for the reasons stated in the relevant exploratory analyses in previous sections.

2.5 Species-environment relationships and the landscape-level distribution of T.fluminensis

From an invasion ecology and biodiversity point of view, the landscape can be viewed as a 'patch-corridor-matrix' mosaic. Viewing a landscape in this way allows spatial analysis of the landscape in terms its constituent spatial elements and their spatial arrangement. This is based on the premise that spatial patterns and spatial processes are linked with respect to their influence on the geographic distribution of a species (Turner, 1989). The patches form the fragmented network of vegetation and remnant habitats scattered across the landscape. The corridors are typically linear areas that are effective dispersal conduits. They may be natural, e.g. rivers, streams and riparian areas, or a result of human modification of the landscape, e.g. hedgerows, roads, tracks and railway lines. The mosaic relates to the dominant land use type surrounding the patches, which in most human-modified landscapes would be agricultural blocks, urban areas, forestry, or horticulture for example. The mosaic may be either hospitable or inhospitable to an invasive plant species, and hence can act as either a barrier or a suitable matrix within which the species may establish and/or disperse to other more suitable patches. Land use/land cover *change* in this context alters the spatial extent, location and arrangement of suitable habitats for a species and alters the condition of those suitable habitats due to various forms of land use-related disturbances and degradation over time.

At this scale, the analysis explores links between aspects of *Tradescantia's* known invasion strategy and landscape configuration and pattern. Factors that relate habitat suitability for *Tradescantia's* spread are explored (discussed in Chapter 1, Section 1.2.2). Then natural and human disturbance patterns are described and the potential for mobility of propagules through landscape level dispersal corridors is assessed. Spatial proximity indicators (produced using Geographic Information Systems, GIS) are used to assess the potential for passage of propagules from source populations in urban and other sites to dispersal conduits. Propagule pressure, i.e. the number of propagules introduced to a site, also becomes more important at the landscape scale: the greater the number of propagules, the greater the chance of propagules dispersing, establishing, and persisting (Lonsdale, 1999, Rouget and Richardson, 2003). The early stages of invasion are constrained by the availability of propagules to utilise suitable sites, and high propagule pressure can, in some instances, outperform as a predictor of invasive species cover than any suite of environmental factors (McKinney, 2002; Rouget and Richardson, 2003; Foxcroft et al., 2004). This is important when assessing the relative effects of climate and land use changes and the suitability for *Tradescantia's* distribution. Finally, the discussion of Section 2.4.3 is also revisited, as it was found that there was a need for land cover/habitat spatial data at a finer spatial resolution than was available at the national-scale, in order to fine tune the association of *Tradescantia* presence observations with land use/land cover.

The Western Bay of Plenty was selected as a landscape for the case study and will be further described in Chapter 4 with regard to land use change scenarios. In terms of indigenous vegetation, this sub-region is heavily fragmented and currently with ≤ 10% remaining (see Figure 2.8 of this Chapter). In this context, most of the lowland indigenous vegetation is in the form of remnant patches of bush, or riparian strips and gullies that were historically inaccessible for vegetation clearance. By contrast upland indigenous vegetation is comprised of relatively intact tracts of indigenous vegetation. Section 2.5.1 will look at habitat suitability indicators for *Tradescantia*.

2.5.1 Habitat suitability for *T.fluminensis*

Suitable habitats at the landscape level were delineated using the ECOSAT riparian classification. 'Patches' in this classification relate to riparian woody vegetation, non-riparian woody vegetation, bare ground and herbaceous riparian vegetation; 'corridors' relate to the river and stream network (that is also spatially adjacent to the 'riparian woody vegetation' class) and non-riparian herbaceous vegetation is the surrounding 'matrix' (representing agricultural and horticultural land).

In Section 2.2, *Tradescantia* was described as a 'symptomatic invader' that responds primarily to disturbance, nitrogen and light gradients. To relate these resource requirements to localised landscape-level pattern directly is not a precise process, unless large amounts of empirical spatial data across resource gradients are available. Such data would be important in process-based modelling of species spread at localised spatial scales (for example at the individual patch or paddock-level; Kriticos, 2003c). However, landscape-level indicators derived using remote sensed imagery, Geographical Information Systems and spatial statistics (Gustafson, 1998; Lausch and Herzog, 2002) can be used instead, to approximate landscape structure, composition and resource gradients in species distribution modelling (Forman and Godron, 1986; McGarigal et al., 2002). When applied to invasive species, typical indicators relate to two priority areas: (1) suitable habitat types and (2) spatial extent and location of disturbances (human and natural) (Tiner, 2004; With, 2002; Rouget and Richardson, 2003; Guisan and Zimmerman, 2000). Indicators include land cover classes/habitat types, species richness, climate, road networks, topography (elevation, slope, and aspect), nutrient and soil gradients, (Moffatt and MacLachlan, 2004; Higgins et al., 1999). They are particularly relevant where on-going land use changes cause the encroachment of residential, industrial and commercial developments onto natural areas in mixed used landscapes and in assessing future scenarios of landscape-level changes (Monticino et al., 2007; Bär and Löffler, 2007).

The use of landscape indicators can offer insights about the influence of human activities on surrounding ecosystems and characterise attributes of habitat and resource gradients (Lauch and Herzog, 2002; Gergel et al., 2002). The usefulness of any spatial indicator will ultimately depend on the response variable (in this case, the spatial distribution of *Tradescantia*), the strength of the relationship between the indicator and the response, and the relative importance of other strong controlling variables such as climate and topography. Simple indicators that describe human influence or habitat characteristics appear to be effective also (Gergel et al., 2002). For example, determining the amount of natural habitats and the human-altered habitats can often relate well to concentrations of nutrients and other pollutants (Gergel et al., 2002; Jones et al., 2001).

In the following sections several landscape-level indicators are used to assess the invasibility of the case study landscape. The most appropriate indicators were then selected to use in the species distribution modelling exercise in Chapter 3. The spatial indicator data layers that were selected for exploratory analysis are shown in Table 2.6.

Landscape-level Indicator	**Derivation**	**Spatial data type**
Habitat		
Riparian	ECOSAT	Figure 2.22
Woody non-riparian: Edge influenced patches	ECOSAT riparian: area <9ha (Young and Mitchell, 1994).	Figure 2.24
Riparian woody	ECOSAT riparian	Figure 2.25
Embedded Patches	ECOSAT Area>9ha for riparian woody and non-riparian woody	Figure 2.26
Disturbance		
<u>Human-influenced</u>		
Urban	Land Cover Database (Class1)	Polygons
Proximity to urban	Euclidean distance to LCDB2 Class 1	Figure 2.29 (15m)
Roads and tracks	National dataset	Polyline
Proximity to Road and Tracks	Euclidean distance to National dataset	Figure 2.32 (15m)
Relative nitrate nutrient	Land cover Database 2) - Aggregation of land cover classes based on nutrient risk ranking by Quinn et al., (1997)	Figure 2.33
<u>Natural</u>		
Streams	Stream network	Figure 2.34
Proximity to streams	ArcMap Spatial Analyst: Euclidean distance to Stream network	Figure 2.35 (15m)
Flood risk	Stream network	Figure 2.37 Polygon
Total: 14 spatial indicators		

Table 2.6 The list of landscape-level spatial indicators used to assess spatial associations with *Tradescantia* distribution.

2.5.1.1 Exploratory Analysis

Firstly, the landscape habitats were explored in terms of area and percentage area statistics for the following classes:

1) Woody non-riparian vegetation (native vegetation indicators)
2) Riparian woody vegetation (remnant native and planted exotic woody vegetation, e.g. willow species)
3) Herbaceous non-riparian - pasture and horticultural orchards
4) Riparian herbaceous – pasture to stream bank of other depleted herbaceous vegetation

The values provided in Table 2.7 are indicators of the percentage of edge habitat to core habitat areas (protected within larger patches) for woody non-riparian (10% and 90% respectively) and riparian woody (42% and 58%). Aggregate results for woody non-riparian and riparian woody classes are provided. They show that riparian vegetation has a higher percentage of edge habitat than does non-riparian vegetation, making it highly invasible. Depicting size of patches is another effective indicator of edge influence. This shows that the number of patches in the riparian woody vegetation class that are completely edge influenced is less than half (27%).

Habitat Variable/Indicator	**Total Area (ha)**	**% Area**
a) Total Edge Area vs Core Areas of all Patches		
Woody non-riparian edge	49134.5	10
Woody non-riparian cores	5723.3	90
Riparian woody edge	15861.4	42
Riparian woody cores	11321.7	58
b) Patches with Area ≤ 9ha vs > 9ha		
Woody non-riparian ≤ 9ha	7418.0	14
Woody non-riparian > 9ha	47439.8	86
Riparian woody ≤ 9ha	7432.6	27
Riparian woody > 9ha	19750.5	73

Table 2.7 Total area of edge habitat versus Total area of core habitat among all patches in the case study area, for the non-riparian woody class and the riparian woody class. b) Patches with area ≤ 9ha (edge-influenced) and patches > 9ha (have some core habitat) in the case study area.

Habitat suitability with respect to the riparian classification (Figure 2.22 and 2.23) indicates that *Tradescantia*'s distribution is associated primarily with woody non-riparian vegetation (typically indigenous forest vegetation), herbaceous non-riparian vegetation, riparian woody vegetation and riparian herbaceous vegetation classes. Healthy riparian zones would be represented by intact and extensively connected woody riparian vegetation that acts as a riparian buffer zone (Auseill, 2003). However, in the case study area, this riparian woody vegetation is heavily depleted and fragmented in the lowland areas (see Figures 2.24 and 2.25). Hence, the extent of remaining lowland woody non-riparian vegetation and riparian woody vegetation classes are indicators of the riparian vegetation condition in this landscape.

The herbaceous non-riparian vegetation and herbaceous riparian vegetation are indicators of human land use pressure and modification at the landscape-level (Auseill, 2003). From field observations and visits to the case study area these observations of *Tradescantia* are more likely to represent infestations in horticultural kiwifruit orchards where they grow in the under-canopy of the kiwifruit vines beside the mown grass strips (Plate 2.2). *Tradescantia* will continue to grow there indefinitely, unless it is sprayed (pers comm., Laurie MacDonald, Environment Bay of Plenty).

Plate 2.2 *Tradescantia* growing directly under the kiwifruit vines in horticultural land (Photo taken by author).

Figure 2.24 shows that most *Tradescantia* observations are located in patches that are <9ha in size, or in other words, considered to be edge-influenced. Such patches are likely to have more light entering sub-canopy levels, increasing suitability for *Tradescantia*. These edge-influenced patches are prevalent in the lowland areas, whereas upland patches are typically >9ha (Kaimai Ranges and extensive gully vegetation). Figure 2.25 shows the ‘linear dendritic network’ or dispersal corridors that the riparian woody vegetation class provides at the landscape-level. It also shows that this suitable habitat class is predominantly

100% invasible/vulnerable in lowland areas (i.e. all patches are <9ha in size). Invasive species are consistently associated with riparian areas, in particular downstream sites, and with the intensification of agricultural activities surrounding the river corridor (Ferreira and Moreira, 1995; Tabacchi et al., 1996; and Tabacchi and Planty-Tabacchi, 1998). They have also been related to human modification of river corridors and fragmentation of the riparian forest (Chauvet and Decamps, 1989), creating new habitats for herbaceous colonization. Exotic species tend to dominate the pioneer patches in the riparian zones after floods (Decamps, 1993). Riparian areas could serve as 'staging grounds' for exotic species to invade new landscape areas, or they may simply harbor exotic species that cannot survive elsewhere (DeFerrari and Naiman, 1994). Figure 2.24 indicates that patches >9ha of the riparian woody vegetation class are typically embedded within the woody non-riparian vegetation class patches also >9ha. As a result, they are typically buffered by the surrounding woody non-riparian vegetation, reducing their potential invasibility because their size is effectively increased due to adjacent intact woody vegetation.

Core areas of habitat are associated with larger patches in the landscape, and indicate a ‘resilient’ patch. Figure 2.26 shows that most riparian woody patches > 9ha in size are embedded within the intact woody non-riparian areas, making them less invasible than other riparian woody vegetation, due to the natural buffer protection by adjacent woody non-riparian vegetation. Figure 2.27 indicates that core areas in the case study landscape are typically within protected areas, either administered by the Department of Conservation (as a part of the Kaimai Range Forest Park) or as a part of the network of regional reserves administered by the Bay of Plenty Regional Council. The majority of observations of *Tradescantia*, fall within unprotected, disturbed, areas of the landscape, outside of core areas of vegetation. These observations match well with the known ecology and invasion strategy of *Tradescantia* described in Section 2.2 of this Chapter. As a result, in Section 2.5.2, the distribution of *Tradescantia* is further explored in relation to human and natural disturbance spatial indicators.

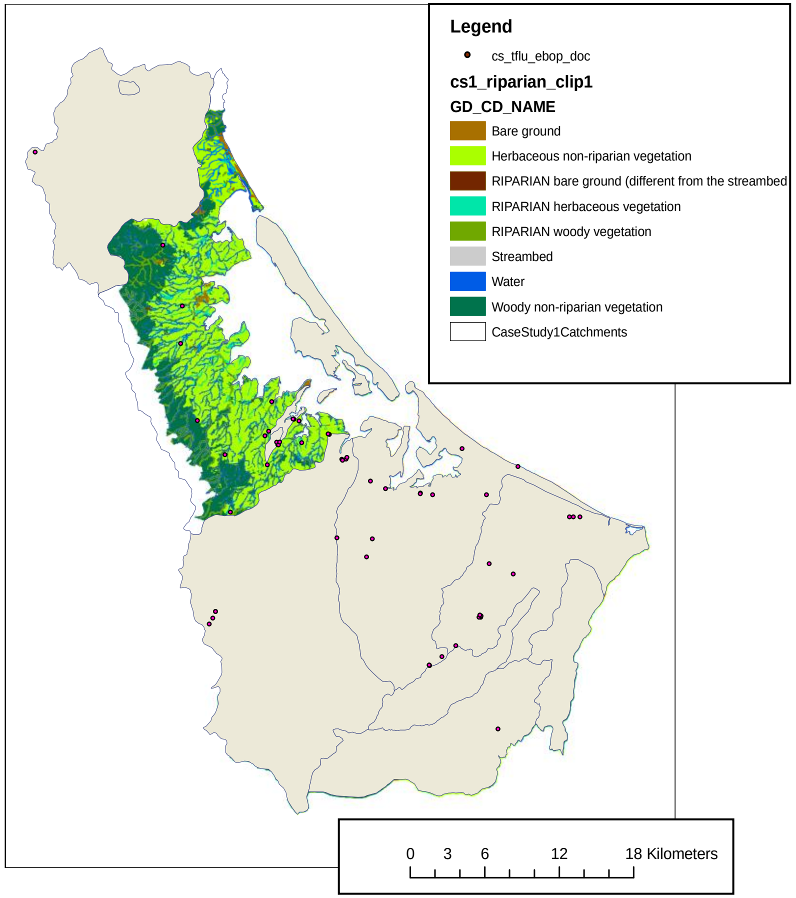

Figure 2.22 The riparian landscape of the Western Bay of Plenty and Tauranga.

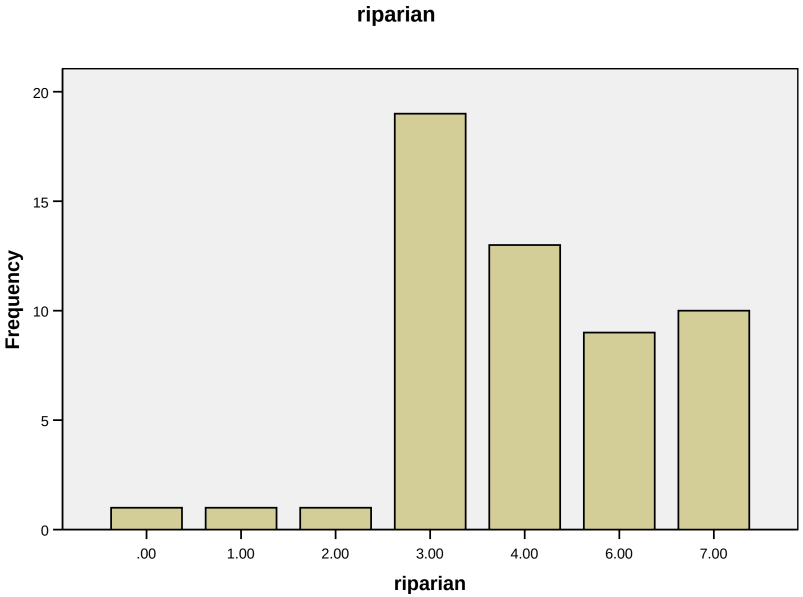

Figure 2.23 Riparian classes versus *Tradescantia* observations. Classes: 0=points outside case study area; 1=water; 2=bare ground; 3=woody non-riparian vegetation; 4=herbaceous non-riparian vegetation; 6=riparian woody vegetation; 7=riparian herbaceous vegetation.

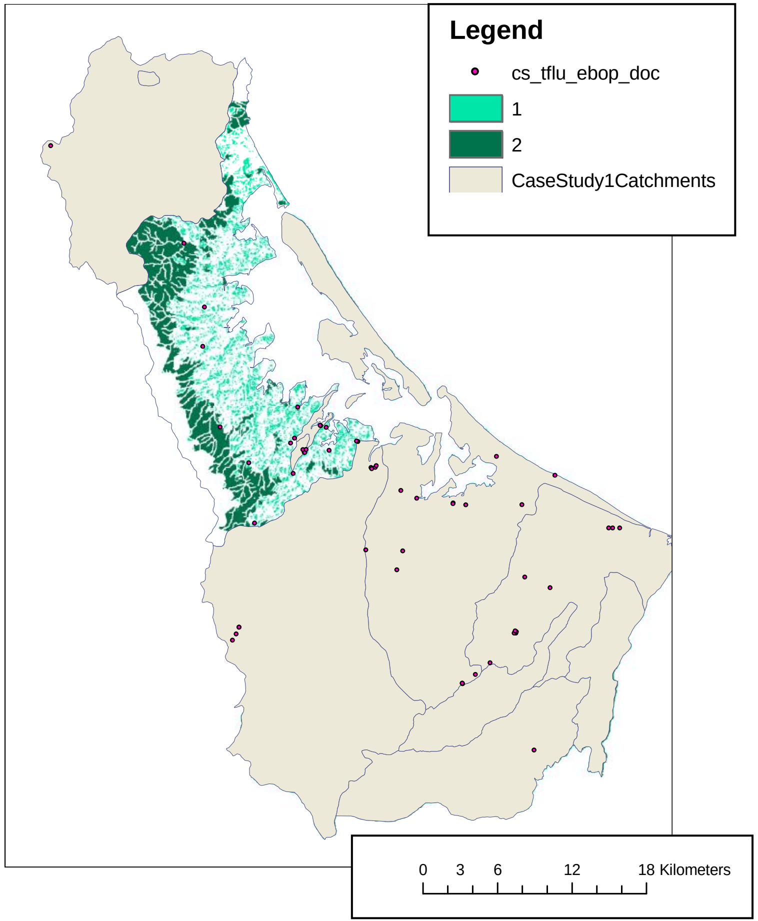

Figure 2.24 ECOSAT-derived, Woody non-riparian vegetation, edge-influenced areas, ≤ 9ha area (1) and ‘in tact’ habitats, >9ha (2).

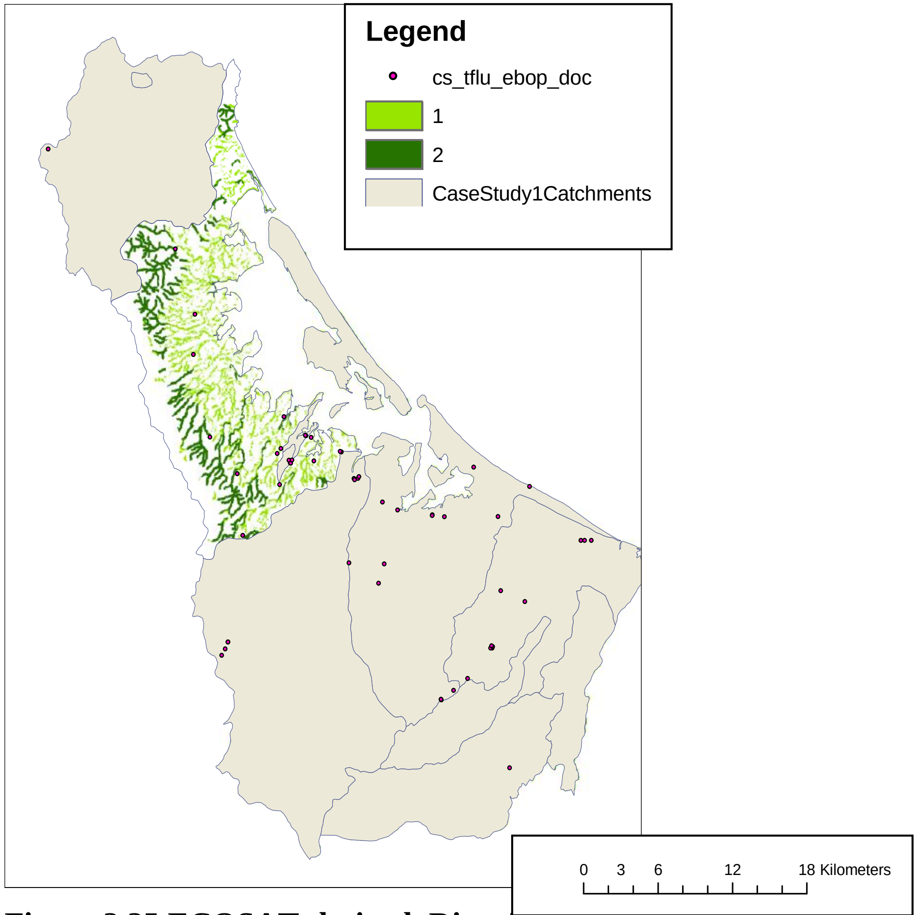

Figure 2.25 ECOSAT-derived, Riparian woody vegetation areas ≤ 9ha area (1) and >9ha (2).

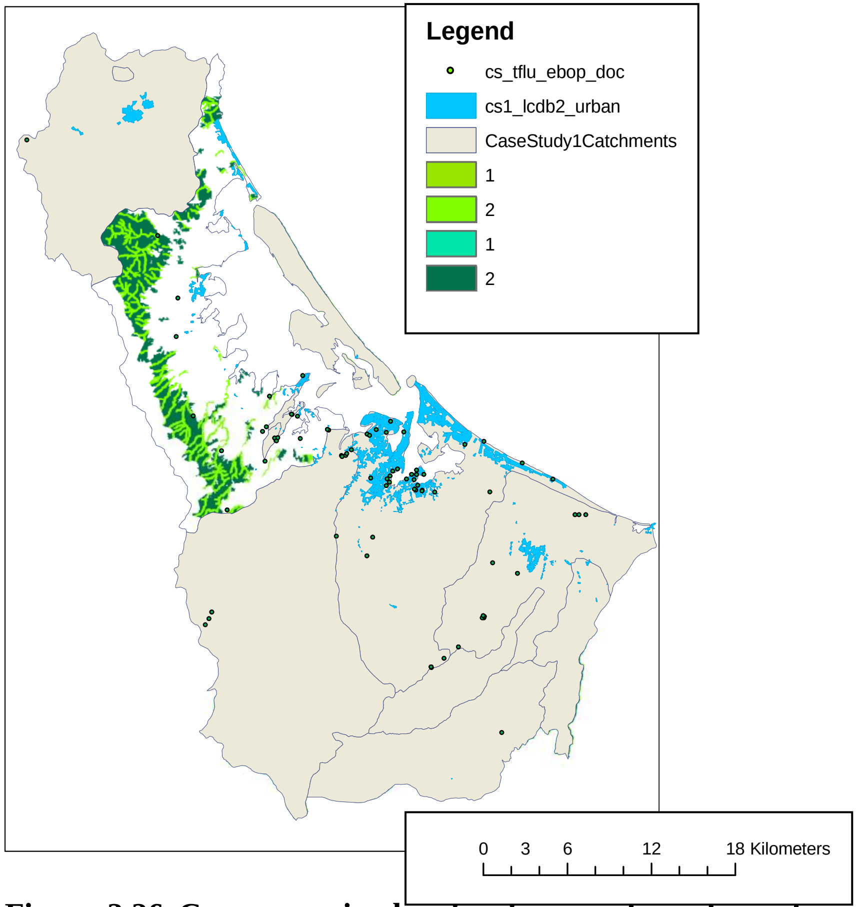

Figure 2.26 Core areas in the riparian woody and woody non-riparian classes. This map shows 'embedding' of riparian woody in woody non-riparian. (Ignore (1)).

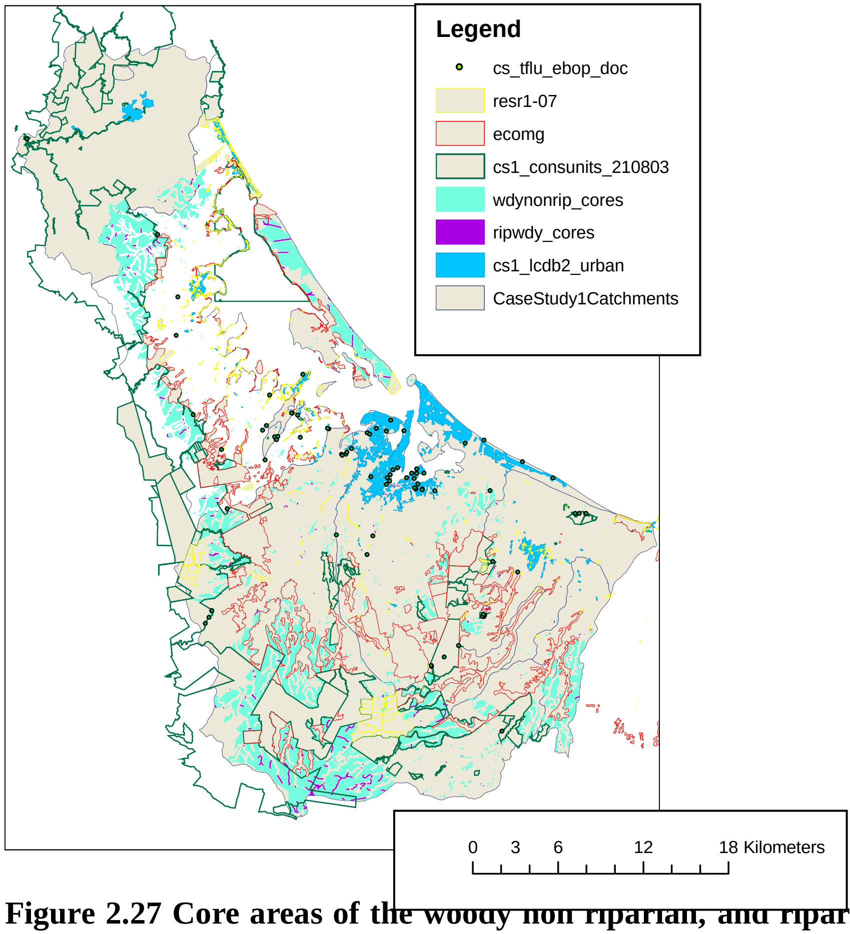

Figure 2.27 Core areas of the woody non riparian, and riparian woody in relation to protected areas in the case study site. It shows that many cores areas are protected.

2.5.2 Human-induced and natural disturbances and *T.fluminensis*

Human-induced disturbances in this context, refers to land use practices and human activities which promote the establishment and persistence of weed growth. The number of possible sources of *Tradescantia* propagules in urban areas (from planting, mowing and dumping activities) is numerous. Urban nutrient releases with stormwater in particular, mean that invasion of nutrient-enriched streams is almost inevitable. Urbanization may thus affect the plant communities associated with riparian areas by favouring species adapted to higher sediment nutrient levels than are naturally present (King and Buckney, 2000; Lowestein and Loewenstein, 2005).

Changes in dominant roadside vegetation, soil moisture, nutrient levels, soil depth, disturbance, and topography are also likely to affect the susceptible to road-side areas to invasion by weeds like *Tradescantia* that are either dumped or planted by roadsides (or in gardens). Roads and streams together appear to serve multiple functions that enhance exotic species invasion in a landscape: as corridor, suitable habitat, and reservoirs of propagules for future episodes of invasion (see Plate 2.3). Species-specific dispersal mechanisms, habitat characteristics, and disturbance history each explain some, but not all, of the patterns of exotic species invasion observed (Parendes and Jones 2000).

Natural disturbance, in this context, refers to floods from local streams or rivers. Regardless of the effects of nutrient enrichment, exotic species cannot invade a stream unless viable propagules of the species are present. The presence of propagules is often dependent on human habitation in nearby areas (Clements 1983). Flowing water has been shown to be an excellent agent for the transport of seeds, rhizomes and other vegetative fragments both longitudinally downstream and laterally between banks on either side of a river or stream. Macdonald and Frame (1988) maintained that the eradication of the woody species *Lantana* *camara* L. and *Melia azedarach* L., both of which have extensively invaded riparian vegetation in Kruger National Park, South Africa, was virtually impossible because of reinvasion from upstream sources. This observation was also confirmed for *Tradescantia* in the case study landscape, where upstream populations continue to be the source for downstream re-invasions (pers. comm., Laurie Donald, Environment Bay of Plenty).

Plate 2.3 *Tradescantia* heavily invading a stream bank with a degraded riparian vegetation canopy, Hamilton, New Zealand (Photo taken by author).

Buoyancy of propagules and high frequency and abundance in the established vegetation promote this dispersal capacity as well. Vegetative propagules may be disturbed by cutting and mowing activities by humans, or cattle stomping in bush and carrying the propagule in their hoofs into free-flowing water (Boedeltje et al., (2003). As well as providing a means of transport for propagules, rivers also facilitate invasion along their margins through provision of suitable habitat for colonizing species. Because the river channel represents a permanent “light gap” allowing sunlight to reach the banks, and competition from previously existing species is much reduced by flood disturbance (Hupp and Osterkamp, 1996; Kalliola and Puhakka, 1988), river banks are prime sites for seedlings of invasive species to germinate and become established. In addition, continual replenishment of nutrients from deposited stream sediments and the ready availability of moisture can result in rapid growth of pioneer species like *Tradescantia*. In many cases such sites are akin to 'ruderal' disturbed sites. Ellenberg (1988) cites several examples of invasive species which have migrated along central European river valleys, including several species of the genera *Solidago, Aster* and *Helianthus* as well as *Impatiens glandulifera* Royle and *F. japonica*. Similarly, Thébaud and Debussche (1991) found that the distribution of seedlings of the colonizing ash *Fraxinus ornus* L. along the Hérault and Vis Rivers in southern France was primarily determined by flood-related factors.

In the case of *Tradescantia*, propagules are vegetative fragments, derived from breakage of the weak above-ground shoots, either from an uprooted plant or any length of a plant fragment. Figure 2.37 shows *Tradescantia* distribution in relation to flood risk, showing higher prevalence of *Tradescantia* in 'high' flood risk areas. Compared with most other vegetative propagules, such as tubers or rhizomes, stem fragments can be detached from the mother plant at any time of the year (Riis and Sand-Jensen, 2006) and downstream establishment of the species is often reliant on upstream source populations for propagules (Riis and Biggs, 2001). Stem detachment is attributed to sediment mobility during high flows and disturbance by animals such as cattle. Often human weed cutting activities also dislodge plant fragments in large volumes, which get released into the waterways (Riis and Biggs, 2001) As peak flows in streams are erratic and may occur at any time of year,, they are likely to favour spread of species which are able to produce propagules such as vegetative stems rather than specialized seeds which are seasonal (Riis and Sand-Jensen, 2006; Riis et al., 2001).

Distance of movement from the point of detachment is a function of the buoyancy of the vegetative fragments, which varies with species (Riis and Sand-Jensen, 2006). Figure 2.28 illustrates the exponential decline in drifting stem fragments with distance from a point of release (after detachment) for two submerged aquatic species. While *Tradescantia* would be considered a terrestrial riparian species, it is expected that its vegetative fragments would follow the same trend as these two aquatic species for exponential decrease with distance from point of release. Therefore the number of infestations along a river/stream length that could provide fragments/propagules after disturbance would influence the risk of invasion at a given point downstream.

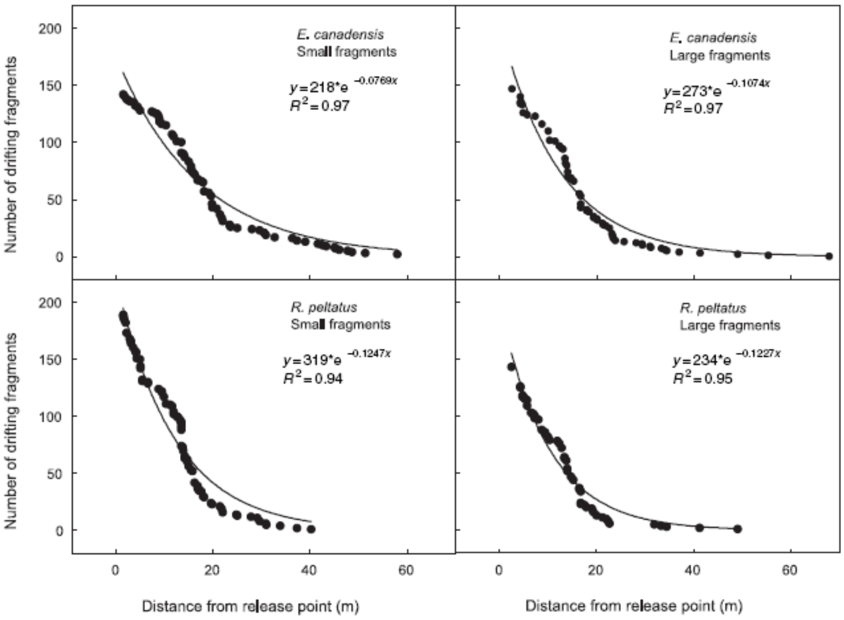

Figure 2.28 An example of hydrochorous (water-borne) movement of vegetative fragments of the plants *Elodea canadensis* and *Ranunculus peltatus.* There is exponential decline of stem fragments with distance along a 300m stream reach (Source: Riis and Sand-Jensen, 2006, pg. 283, used with permission).

2.5.2.1 Exploratory Analysis

Figures 2.29 and 2.30 shows that *Tradescantia* is observed mostly in either fully urban areas or with proximities <1000m. This relates well with the relationship found by Sullivan et al. (2004) where the highest number of naturalised non-indigenous species was found within <0.5km of urban areas (see Figure 2.31). The urban centres are Tauranga (the largest city), Katikati, Te Puke, Waihi, Papamoa, Mount Maunganui and Kaimai. These will be further described in the context of land use change in Chapter 4. Tauranga is the largest source of *Tradescantia* with 30 of the total 79 observation found there. Other sites are scattered in the peri-urban to rural areas, likely associated with plantings in residential gardens on lifestyle blocks and farms. As shown in Figure 2.32, almost all the observations of *Tradescantia* are close to roads or DoC tracks, with no observations in areas with no roads. This relationship with roads and tracks is perhaps the clearest spatial indicator of the association of *Tradescantia* distribution with disturbed sites and those in combination with human settlement.

Given that *Tradescantia* responds positively to nitrate nutrition, Figure 2.33 was created to assess the distribution of land cover classes in order of increasing relative nitrate enrichment. In this context, the hierarchy of nitrate risk can be represented as: orchards, vineyards and other perennial croplands > riparian areas > urban areas > early successional forests and shelterbelts > pine forests > intact indigenous and broadleaved forests. The low number of observations of *Tradescantia* perhaps precludes an adequate analysis of the association with land cover classes to nitrate enrichment, however, it is evident that there are a number of observations in the ‘Orchard and other perennial’ class and the ‘Urban’ class as expected. Since all the high risk classes for nitrate enrichment are represented either by the riparian habitat network, the urban, roads and streams networks, these layers are used as proxies for nitrate enrichment, without using a nitrate spatial layer per se, as this dataset was not available. Figure 2.34 and 2.35 show *Tradescantia* in association with proximity to streams (also see Plate 2.4), and Figure 2.36 confirms that most observations were within 200m of a stream. Though there would be many local barriers preventing propagules from traversing 200m to reach a stream, if they were transported there via stormwater drains and channels, and garden waste dumping, this distance would be easily traversed. Many of the sites were in lowland high flood risk areas (Maps 2.19 and 2.21), and floods also could easily transport propagules over distances of 200m.

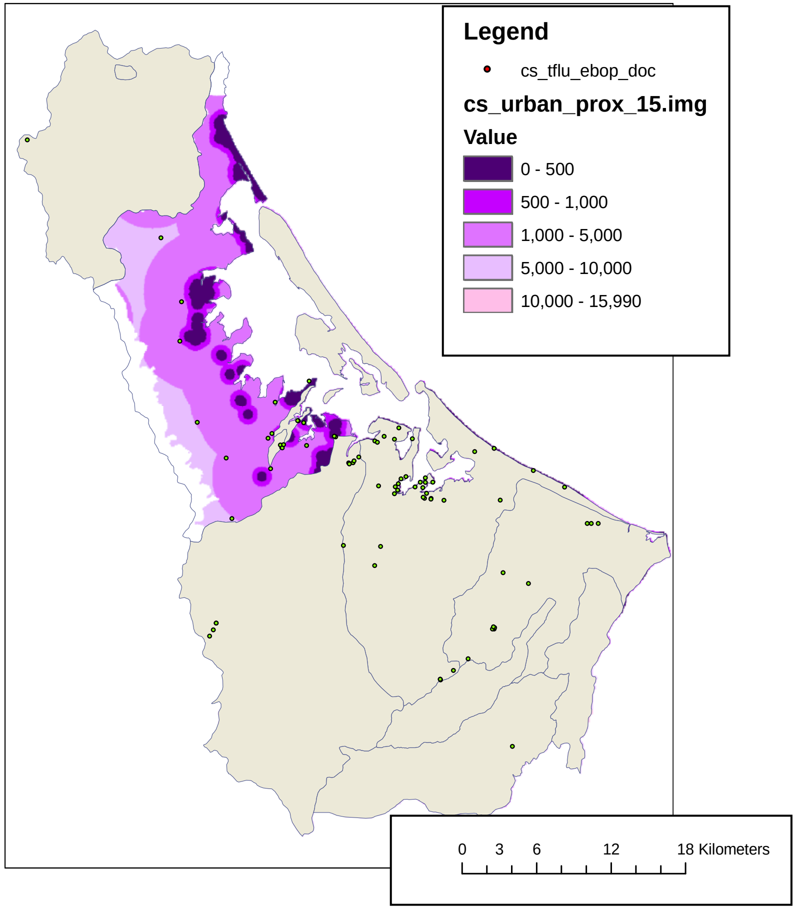

Figure 2.29 Proximity to urban areas versus the distribution of *Tradescantia*.

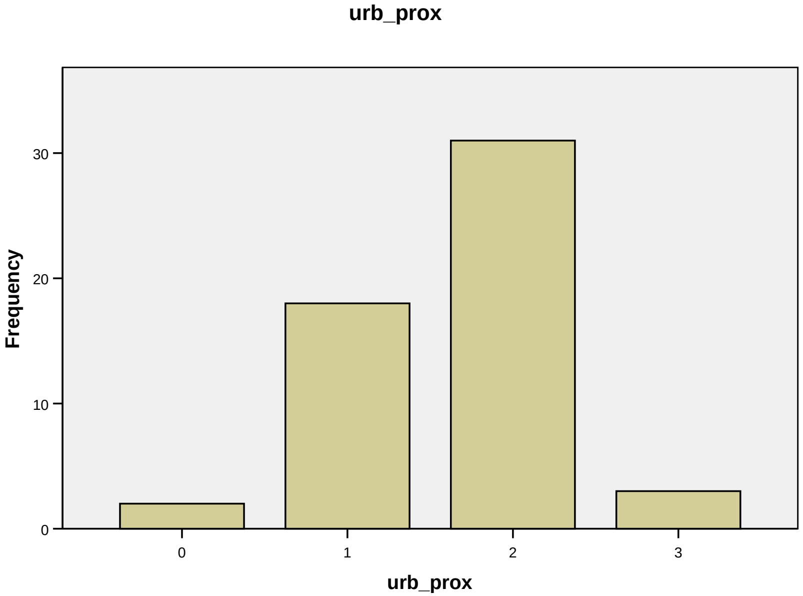

Figure 2.30 Frequency of *Tradescantia* observations within distance classes from urban centres. Classes are 0=0m; 1=500m; 2=1000m; 3=>5000m (Based on >50 observations of *Tradescantia*).

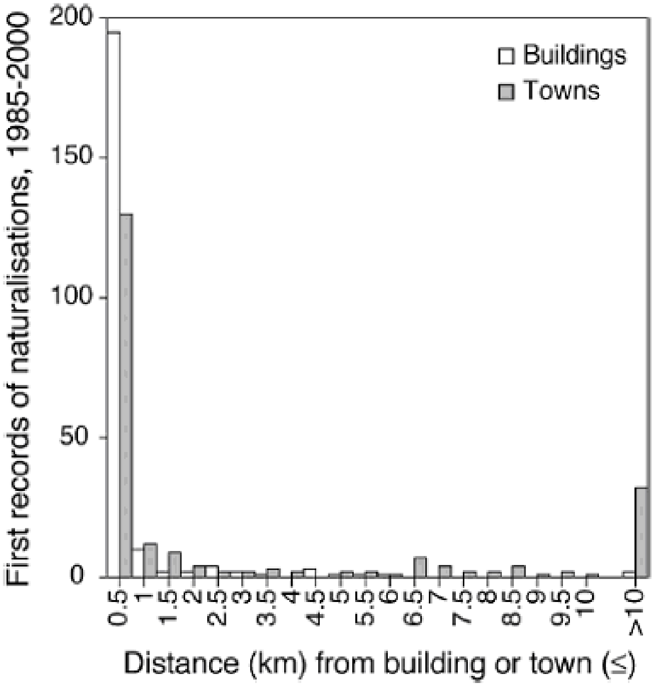

Figure 2.31 Distance to towns and buildings and records of first naturalised plants, some of which become weeds (Source: Sullivan et al., 2004, used with permission).

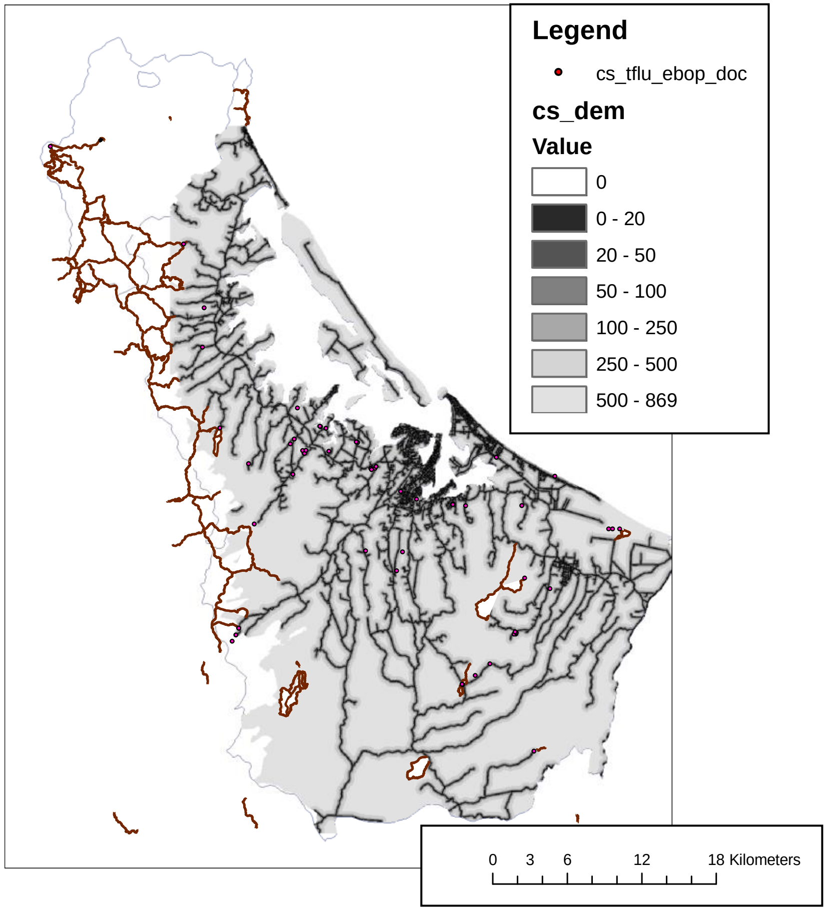

Figure 2.32 Proximity to Roads versus the distribution of *Tradescantia*.

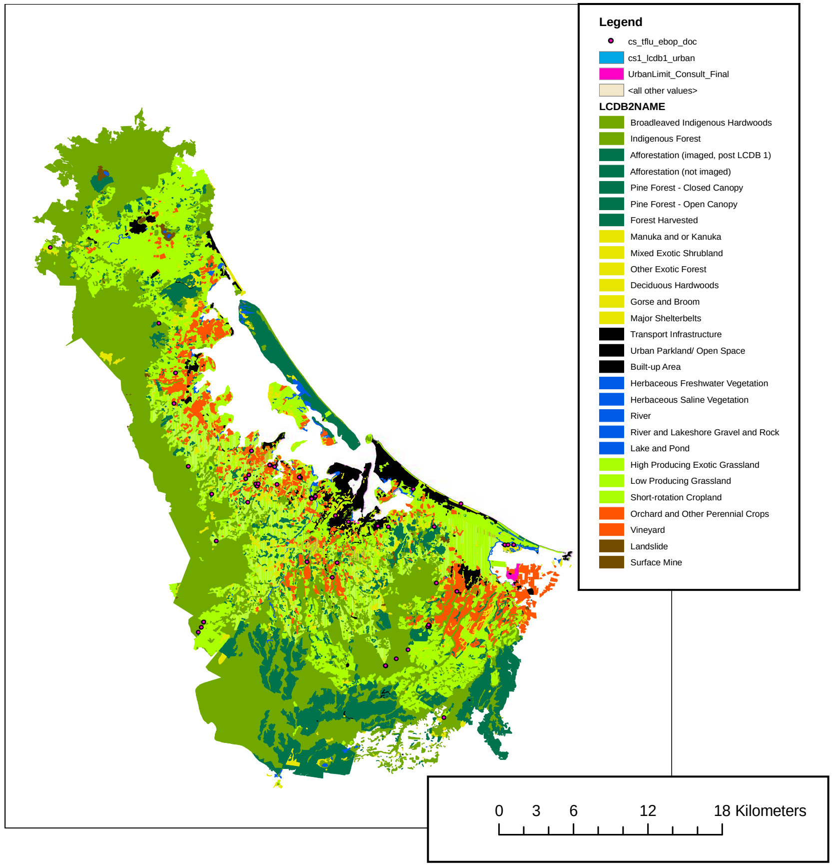

Figure 2.33 Relative nitrate nutrient by land cover class at the landscape level (increasing from top to bottom of legend).

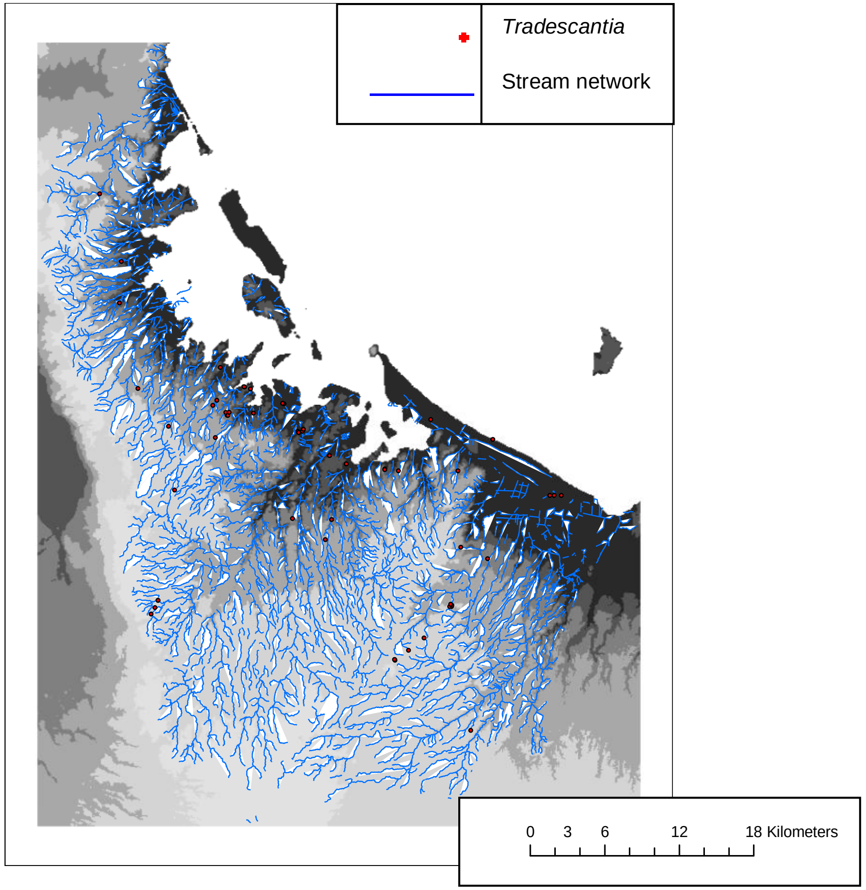

Figure 2.34 The stream network and *Tradescantia's* distribution. Streams provides dispersal opportunities for invasive species like *Tradescantia*.

Plate 2.4 Localised stream water turbulence adjacent to stands of trailing *Tradescantia*, Hamilton, New Zealand (Photo taken by author).

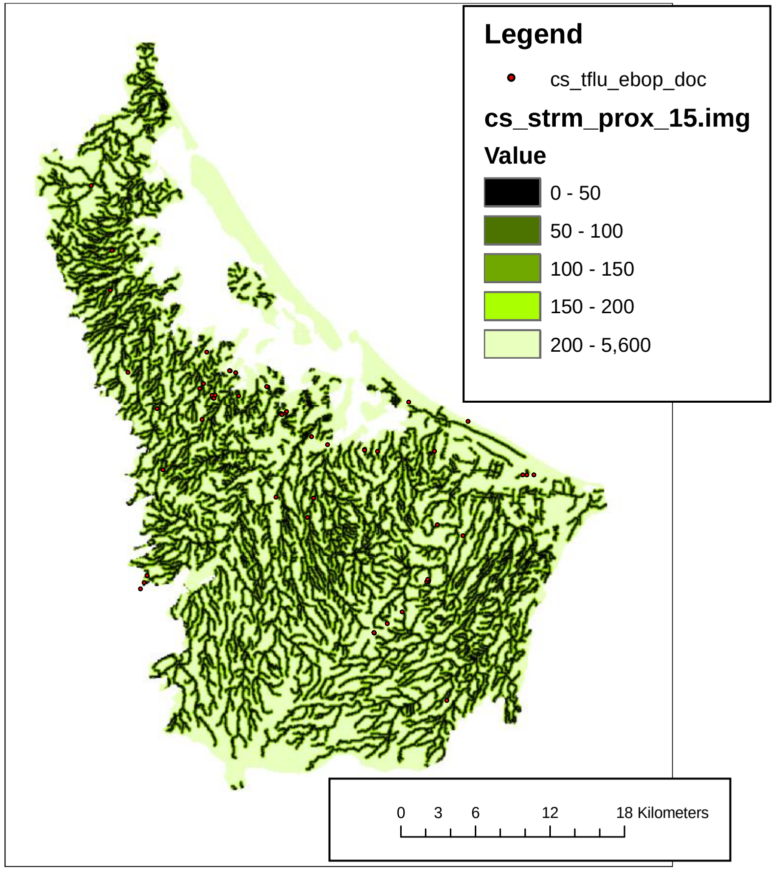

Figure 2.35 Proximity to streams (m) in the case study area versus *Tradescantia's* distribution.

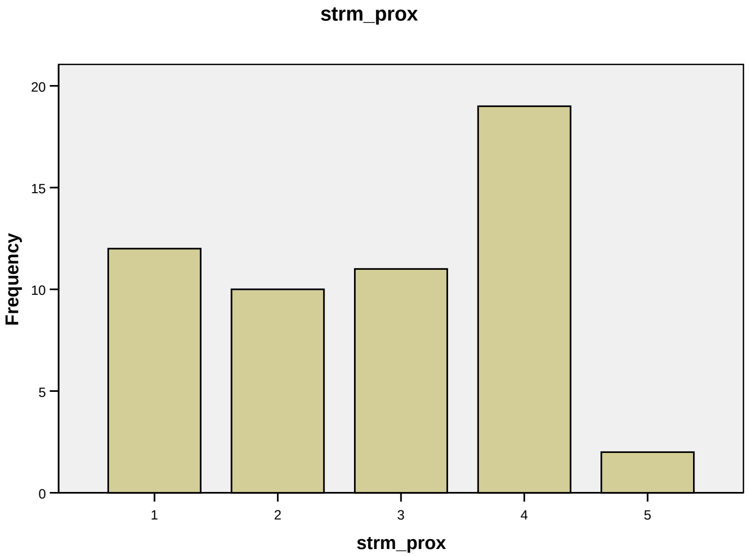

Figure 2.36 Frequency of observations of *Tradescantia* versus proximity to streams. Class1=0-50m; 2=50-100m; 3=100-150m; 4=150-200m; and 5≥200m.

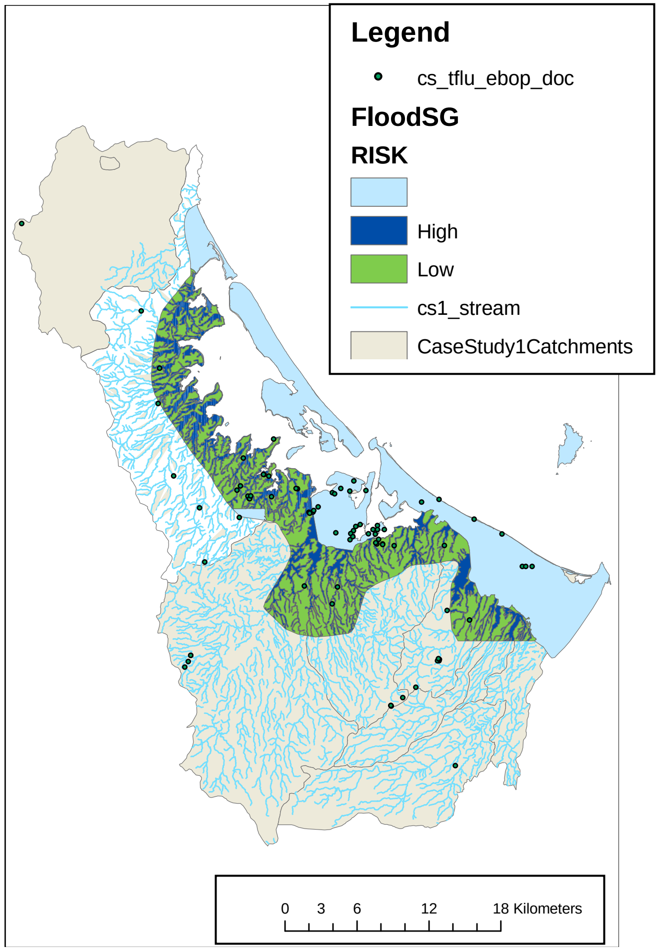

Figure 2.37 Flood Risk in the Case study area. The light blue areas represent the coastal settlements and therefore are exposed to the highest risk (Source: Environment Bay of Plenty).

2.6 Conclusion

In terms of developing the Integrated Assessment Methodology (through a Composite Invasibility Index) at the national and landscape-levels, *Tradescantia fluminensis* was chosen as a model species for the following reasons:

(i) Distribution range: *Tradescantia* is a widespread species and is likely to have populated most of its realised niche (current potential distribution based on suitability of invaded habitats globally), well beyond its native distribution, SE Brazil. This point is of significance in modelling future climate and land use changes, which are likely to further range expansion of the realised niche in New Zealand, (Guisan and Thuillier 2005).

(ii) Climate: Invasibility of habitats by *Tradescantia* is influenced by potential sensitivity to minimum temperature and drought (or extreme events of these variables such as frost frequency and AWD/water balance) both of which are likely to change with climate change; *Tradescantia* is also dispersed by hydrochorous action of streams and rivers, which is exacerbated by flood events. Floods are associated with extreme precipitation events which can be modelled, both for baseline and future extreme event scenarios.

(iii) Land-use: Human-induced disturbances such as fragmentation, edge creation, nutrient changes, development of ruderal sites and greenwaste dumping, are all associated with land use change.

(iv) Landscape: *Tradescantia* is a widespread invader of disturbed edge habitat in the landscape (including riparian, bush and forests), and lowland fragments of reduced size (<9ha);

(v) Dispersal: only vegetative reproduction is observed in New Zealand, therefore dispersal pathways are limited to humans, water or cattle, which are easier to model than more stochastic processes such as wind dispersal.

(vi) Resource requirements: nitrophilous habit and invasion of nitrogen enriched sites (naturally and anthropogenically disturbed), high acclimation to light availability (also linked with anthropogenically modified edge habitats).

The variables selected for the species distribution modelling are as shown in Table 2.8.

Selected Indicator	**Scale, Resolution**
Climate	
Temperature minimum (MTminJ-A)	National, 100m
AWD	National, 100m
Habitat	
Land cover (70 classes)	National, 100m
Riparian (7 classes)	Landscape, 25m
Proximity to urban	Landscape, 25m
Proximity to roads	Landscape, 25m
Proximity to streams	Landscape, 25m
Total: 7 variables	

Table 2.8 Selected variables/indicators for the species distribution modelling.

Elevation was not selected as it is known to be highly correlated with minimum temperature. Slope was not selected as slope variations in *Tradescantia* distributions are likely to be primarily due to the spatial distribution of human settlement patterns across landscape, rather than directly associated with slope. Frost free period was also not selected for the modelling activities because it is also likely to be linearly correlated with mean minimum temperature. As a result only mean minimum temperature (July-August) the coldest months was selected for the modelling. AWD was also selected because there was a clear association with areas where *Tradescantia* showed no ‘presence’ observations, i.e. in dry and heavily modified agricultural plains such as in Hawkes Bay, Wairarapa, Canturbury Plains and Central Otago Plains. The *Tradescantia* observations were prevalent where AWD was 0. As a result AWD was also chosen as a variable/indicator particularly to delineate areas unsuitable for *Tradescantia*. Land cover data was also shown to have a clear association with the variation in observations of *Tradescantia*. However, at the national level, land cover is not expected to improve the species modelling, according to several authors who suggest that climatic factors approximate species distributions at larger scales than habitat/land cover variables (Pearson and Dawson, 2004).

At the landscape level, the habitat variables was changed to include more detailed riparian habitat data, and disturbance indicators. As a result, proximity to urban areas, proximity to roads, and proximity to streams were chosen as landscape-level variables for the species distribution modelling. A further reason for using these variables is that proximity to roads and proximity to urban areas can both be easily changed according to future changes in urban areal extent and road network changes. These changes will be a major component of the land use change scenario development in Chapter 4.

Chapter 3 will proceed to select and implement the appropriate species distribution modelling methods for the distribution of *Tradescantia* at two scales, national and landscape, based on the 7 variables selected in Chapter 2. This will form the baseline distribution which will then be perturbed with climate and land use change scenarios (Chapters 4-6).

3 Chapter 3: Modelling the spatial distribution of *T.fluminensis*

3.1 Introduction

The objective of this Chapter is to model the spatial distribution of *Tradescantia*, to produce the *baseline spatial distribution* at two scales: national (New Zealand) and landscape level (Western Bay of Plenty and Tauranga sub-region). This baseline spatial distribution will provide the basis for comparison with the projected future distribution of *Tradescantia* under climate and land use changes scenarios in Chapter 6. In this chapter, the objectives will be met by:

1) Reviewing and identifying appropriate modelling methods for invasive species distribution mapping;
2) Implementing the appropriate modelling methods based on the species-environment relationships derived from Chapter 2;
3) Producing the baseline spatial distribution of *Tradescantia* at the national and landscape levels; and
4) Validating the baseline species distribution based on observed spatial distribution of *Tradescantia*.

3.2 Species Distribution Modelling: Ecological Concepts

Species distribution models, now widely in use with biogeographers and ecologists (Guisan and Thuillier, 2005), have been developed to allow a probability of occurrence to be predicted in a location where no species information (or observations) are recorded (Zaniewski et al., 2002). Such models are static and probabilistic in nature, since they statistically relate the geographical distribution of species or communities to their present environment (Guisan and Zimmermann, 2000). A range of Species Distribution Models (SDMs) exists, and with recent advances in powerful statistical techniques and Geographical Information Systems (GIS) tools, the development and use of predictive species and habitat distribution models has grown widely in ecology (Austin, 2007; Austin, 2002; Hirzel et al., 2001; Guisan and Zimmermann, 2000).

Guisan and Thuillier (2005) state that SDMs have been used primarily to investigate the biogeographic distribution of plants and animals for some of the following objectives:

1) Quantifying the ecological niche of a species;
2) Assessing species invasion and proliferation in novel environments;
3) Assessing the impacts of climate, land use and other changes on species distribution;
4) Suggesting unsurveyed sites with high potential of occurrence for rare species;
5) Supporting appropriate management plans for species recovery and mapping suitable sites for species reintroduction;
6) Supporting conservation planning and reserve selection; and
7) Modelling species assemblages (based on individual species distributions)

In order to develop a SDM, certain underlying ecological concepts are drawn upon to form a conceptual framework. These have been outlined by Guisan and Zimmermann (2000, used with permission) and due to their importance to understanding SDMs and interpreting the resultant species distributions or equivalent Habitat Suitability Indices, these ecological concepts are discussed in the following sub-sections 3.2.1-3.2.5.

3.2.1 General patterns in the geographical distribution of species

The theoretical premise of modelling species distributions originates in the field of biogeography. Central to species distribution modelling is exploring the spatial distributional limits of a species, based on *biotic* factors (e.g. competitors) versus *abiotic* factors (e.g. temperature minima, water deficit or soil nitrate concentrations). The physical limits of a species' distribution are attributable to environmental and physiological constraints along direct and resource predictors (or gradients), as per Austin et al. (1984) and Austin and Gaywood (1994). Ecological concepts which help to depict (1) causal versus non-causal factors (i.e. direct versus indirect predictors) or (2) inter-species competition, for fitting static species distribution models are provided in the next sections.

3.2.2 Direct versus indirect predictors

Direct predictors (or gradients) are environmental parameters[21] that are considered to be the causal, driving forces for species distribution and abundance (for example, temperature, soil moisture and pH). Direct predictors have physiological importance, but are not physically consumed by species. Such predictors are generally sampled from digital maps, since they are usually difficult or expensive to measure. From a mechanistic point of view, it is desirable to predict the distribution of biotic entities on the basis of direct predictors. However, they often tend to be less precise than topographic characteristics. Most bioclimatic maps are developed by elevation-sensitive spatial interpolations of climate station data, for example, BIOCLIM and AnuCLIM models (Hutchinson and Bischof, 1983; Daly et al., 1994; Thornton et al., 1997).

Indirect predictors (or gradients) are parameters that have no direct physiological relevance for species performance (slope, aspect, elevation, topographic position, habitat type, geology). They are more easily measured in the field and are more often used than direct predictors because of their good correlation with observed species patterns. The usefulness of indirect predictors integrated in species distribution models is that they usually replace a combination of different resources and direct predictors in a simple way (Guisan et al., 1999). Figure 3.1 shows a conceptual representation of the direct and indirect predictors (or gradients) and their influence on plant growth, abundance and distribution. Landscape-level indirect predictors also influence the spatial distribution of a species, and though these have not been included in this conceptual representation by Guisan and Zimmermann, (2000), they do form an important basis for identifying suitable habitats where a species is distributed at the landscape level (as described in Chapters 1 and 2).

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[21] A 'parameter' in this context is defined as a variable and measurable property whose value is a determinant of a system, for example, temperature and pressure are parameters of the atmosphere. In other contexts however, a parameter is defined as a constant whose values determine the specific form or characteristics of an expression.

One drawback of using indirect predictors is that a model can only be applied within a limited geographical extent without significant errors. This is because in a different region the same topographic position can represent a different combination of direct and resource predictors. This situation is perhaps more relevant to native species in ‘equilibrium’ with the environment, rather than non-equilibrium species, which are still spreading through the landscape, as is the case of most invasive plant species. In contrast, direct and resource predictors are predictive parameters, i.e. the relationship between the predictor and the species distribution is supposedly more physiologically ‘mechanistic’. Therefore a model based on direct and resource predictors is more general and applicable over larger areas. As a result, direct gradients such climatic variables are essential in species modelling, particularly at larger scales and for more generic species modelling exercises.

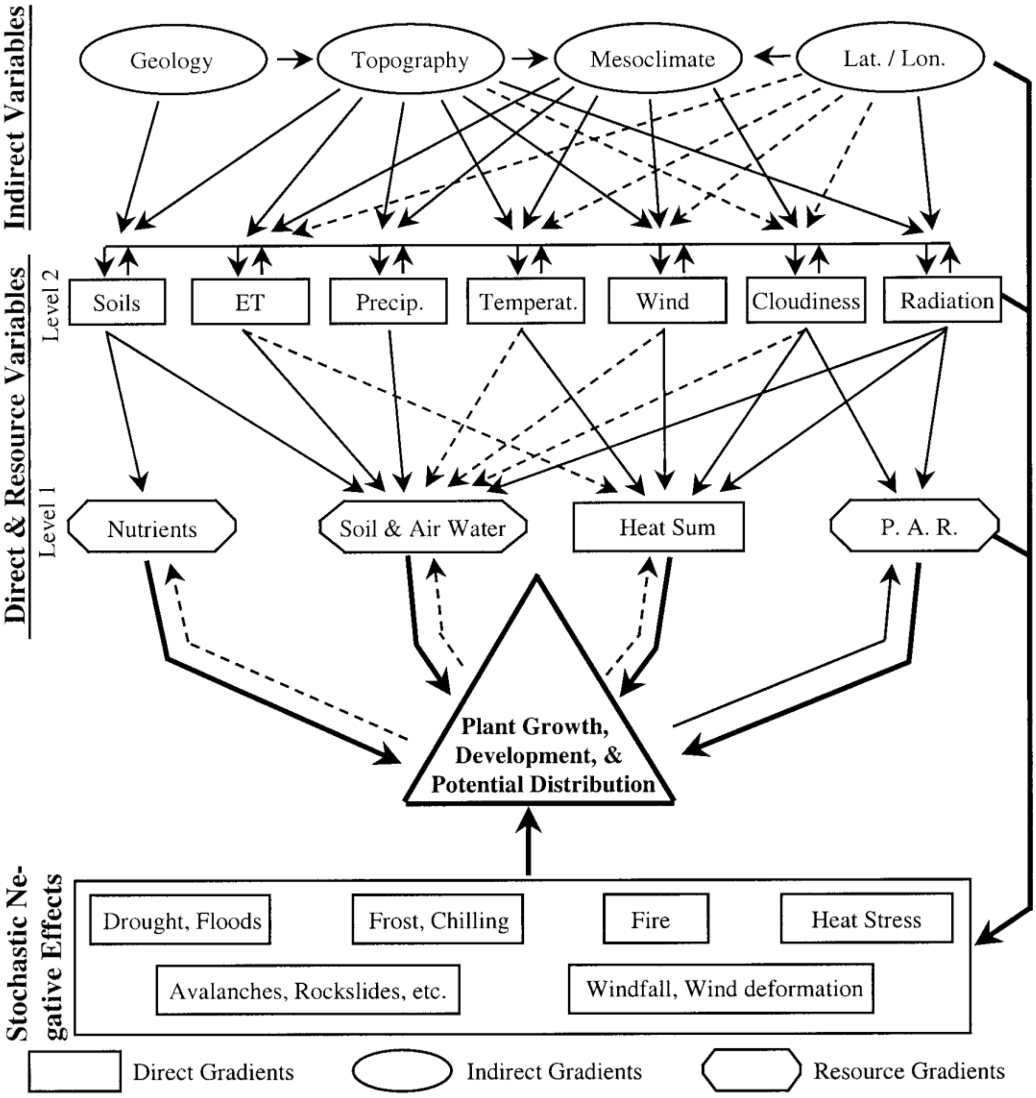

Figure 3.1 A conceptual representation of the direct or resource and indirect predictors (gradients). These have an influencing role on the growth, performance and geographical distribution of vascular plants and vegetation (based on Austin and Smith 1989, In: Guisan and Zimmermann, 2000, pg. 152, used with permission). Here gradients are equivalent to 'predictors' or 'variables' (the measurable parameters that characterise the gradients). For this study, 'landscape-level' predictors are also included as indirect predictors because of their influence on the spatial configuration species distribution.

3.2.3 Fundamental versus realized niche

The *fundamental* niche of a species is the geographical space within which a species thrives across a combination of environmental gradients. It is primarily a function of physiological performance under various ecosystem constraints which limit its presence, growth, prevalence and survival. The *realised* niche, on the other hand, includes biotic interactions and competitive exclusion. It is the 'resultant' niche after negative ecologically-limiting factors, which limit the geographic extent and abundance of a species, are taken into account (Ellenberg, 1953; Malanson et al., 1992; Malanson, 1997).

Simulated distributions predicted from theoretical physiological constraints determine the fundamental niche while field-derived empirical observations determine the realised niche. Static predictive models are generally based on large empirical field data sets and species observations, thus they are likely to predict the *realised (ecological) niche*. Therefore, static predictive models have some limitations when applied in changing environmental situations. The realised niche, when modelled will produce the *realised distribution map* of the focal species.

3.2.4 Equilibrium versus non-equilibrium

SDMs are static distribution models, as they represent the spatial distribution in one time slice and are not based on dynamic process-based simulations. They are developed from simple statistically- or theoretically-derived response surfaces. As a result, they automatically assume equilibrium, or at least pseudo-equilibrium (Lischke et al., 1998), between the environment and observed species patterns. However, this assumption in many circumstances is simplistic, particularly where species are subject to stochastic and episodic disturbance events, or other sources of resource or pollution changes, for instance, which affect the spatial distribution of species. Hence, the non-equilibrium concept is more realistic in ecology (Pickett et al., 1994), because it includes equilibrium as one of several possible states (Clark, 1991). If a model is based on the non-equilibrium concept it is likely to include (i) dynamic and (ii) deterministic and/or stochastic elements. Static distribution models, on the other hand, are conceptually unable to cope with non-equilibrium situations, since they do not distinguish between the transient and equilibrium response of species to a stochastically and dynamically changing environment.

The assumption of equilibrium is less of a limitation for modelling species or communities which are relatively persistent or react slowly to variability in environmental conditions (e.g. arctic and alpine). However, it does represent an ongoing limitation for more non-equilibrium species like invasive plants which are still filling novel ranges, especially in response to changes to climate and disturbance regimes (Dukes and Mooney, 1999 and Vitousek, 1997). At larger scales of species distribution modelling, this limitation is less important, as the effects of localised disturbances and stochastic processes are not often significant at these scales, and usually no detailed knowledge of the physiology and behaviour of the species is utilised. Situations with strong disturbance, human influence, or successional dynamics, as in the case of invasive species, can thus only be modelled with difficulty at large scales; hence there is a need to perform local landscape-level analyses[22], where disturbance and human influence can be incorporated.

Static species distribution models represent only some of the available methods at present (Brzeziecki et al., 1993; Guisan et al., 1999; Lees and Ritman, 1991; Zimmermann and Kienast, 1999). The alternative to static, equilibrium modelling is dynamic simulation modelling (Korzukhin et al., 1996; Lischke et al., 1998). However, since such models require intensive knowledge of the species involved, most of these models can only be used for well-investigated species and habitats.

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[22] It is sometimes possible to include predictive parameters, e.g. ENFA will specifically integrate variables related to habitat, disturbance, human influence and climate, topography etc in producing its final Habitat Suitability Index for a species (which is equivalent to the species' distribution). This is a major advantage of using ENFA as a preferred modelling method in this project.

3.2.5 Species versus community approach

Another major discussion in this field is whether a model is said to be 'gleasonian' or 'clementsian' (Prentice et al., 1992) that is, simulating species either as individuals or as community assemblages respectively (see also Franklin, 1995)[23]. A main argument for individual species-based modelling is the paleoecological evidence that plant species assemblages have never been stable, mostly due to past variations in climate (Webb, 1981; Prentice, 1986; Ritchie, 1986). Modern species assemblages do not have long histories (Davis, 1983; Birks, 1993). Therefore, communities are not likely to move as an entity under changing climatic conditions (Birks, 1986; Huntley and Webb, 1988). Hence, it is argued, modelling species instead of communities comes closer to what is believed to be realistic. An alternative to modelling communities is to simulate a selection of dominant species, and to classify their superimposed distributions afterwards, in order to generate simulated community maps (Lenihan, 1993; Austin, 1998; Guisan and Theurillat, 2000).

Tradescantia is not recorded to have any strong competitive interactions with other species that restrict its spread directly in New Zealand. In such a situation taking an individual 'species-based' approach to spatial distribution modelling is appropriate. However, when predicting future potential distributions based on static models and scenarios of environmental change (for example, climatic change), the same limitations apply to both species and community models: they are based on equilibrium assumptions (between observed response and environmental conditions) and they lack the mechanisms for simulating the individualistic behaviour of species (including seed dispersal, migration, plasticity, and adaptation).

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[23] This discussion is embedded in the community-continuum debate (Clements, 1916, 1936; Gleason, 1926; Cooper, 1926; Whittaker, 1967; McIntosh, 1967; Austin, 1985; Austin and Smith, 1989; Collins et al., 1993).

Although static SDMs have some drawbacks as described above they are the only available method for large scale spatial distribution mapping of species ranges, given that more mechanistic, process-based and dynamic modelling methods are highly species-data intensive and can only be accomplished for smaller areas. Given that a national distribution baseline and future spatial distribution changes with climate and land use changes are to be produced in this thesis, dynamic modelling approaches will not be suitable and so SDMs are chosen instead, as the most suitable modelling approach.

The following section looks at the SDMs in use with a view to selecting the specific ones for modelling the species distribution of *Tradescantia* under baseline and future climate and land use scenarios. The main criterion for suitable models will be their ability to perform using ‘presence only’ species distribution data, given that this is what is available for *Tradescantia* (and for almost all invasive species globally) and their ability to integrate climate and land use change scenarios to project future distributions of *Tradescantia*. This integration is a central part of the methodology and draws on the species-environment associations discussed for *Tradescantia* in Chapter 2.

3.3 Using Species Distribution Models for integrating climate and land use changes

The most commonly used SDMs applied to climate change assessments of species distribution changes (where species distribution change is a measure of ‘climate change impact’ on species or biodiversity) are <u>bioclimatic models</u> (Harris et al., 2006; Heikkinen et al., 2006; Midgley et al., 2002; Pearson and Dawson et al., 2003; and Pearson et al., 2002;). Bioclimatic models include BIOCLIM, SPECIES (Spatial Evaluation of the Climate Impacts on the Envelopes of Species) (Pearson et al., 2002), CLIMEX (Sutherst, 2003; Kriticos et al., 2003a and b; Kriticos 2001; and Wharton and Kriticos, 2004), and other niche based models (Guisan and Zimmermann, 2000; Thuiller et al, 2004; Thuiller, 2003). The niche-based models include Ecological Niche Factor Analysis (ENFA) (Hirzel et al., 2001 and 2002), Artificial Neural Networks (ANNs); the constrained Gower metric (Miles et al., 2004: similar to DOMAIN); classification tree analysis (CTA) (Thuiller et al., 2003); genetic algorithms (GA) (McClean et al., 2005); the generalized additive model (GAM) (Segurado and Araujo, 2004); genetic algorithm for rule-set prediction (GARP) (Stockwell and Peterson, 1999); and the Generalised Linear Model (Thuiller, 2003), all of which use climatically-derived input variables (Pearson et al., 2006).

Species distribution models can broadly be classified, on the basis of their species data requirements, into: (1) species 'presence-only' models; and (2) species 'presence-absence' models. Presence-only models include: Ecological Niche Factor Analysis (ENFA), BIOCLIM and DOMAIN (Brotons et al., 2004; Segurado and Araújo, 2004; Pearce and Boyce, 2006). These methods were developed to allow the use of data where knowledge of absences is inadequate, unavailable or meaningless (for instance, with invasive species which are still filling novel niches) (Carpenter et al., 1993; Hirzel et al., 2002a; and Farber and Kadmon, 2003). Presence-absence models include: Generalised Linear Modelling (GLM), Generalised Additive Modelling (GAM), Classification Regression Tree Analysis (CART) and artificial neural networks (ANN) (Austin, 2007; Araújo et al., 2005; Segurado and Araújo, 2004; Guisan et al., 2002; and Guisan and Zimmermann, 2000). Presence-absence methods generate statistical functions or discriminative rules that allow habitat suitability to be ranked according to distributions of presence and absence of species (Manel et al. 1999, Guisan and Zimmermann, 2000). Almost all SDMs work on the assumption that both 'presence' and 'absence' data are available for the species being modelled; however this assumption is not met for many species. In particular, for invasive species which are still filling their ecological niches in novel environments, it is not clear which areas fall outside their ecological niche (i.e. where absences could be recorded from); for other widespread species it is often impractical to collect absence data given the high level of occurrence.

A general hierarchical framework can be used to guide the development of presence-only models that integrate climatic and other environmental factors to model species distribution. Figure 3.2 shows a schematic of the general hierarchical modelling framework required for species distribution modelling, in particular for invasive species like *Tradescantia* that respond to local disturbance and dispersal.

Bioclimatic models, as mentioned above, in general are particularly suited to climate change assessment of species distribution changes, as they work on the premise that climatic variables are the primary constraint on individual species distributions. This is particularly true of habitat suitability at larger spatial scales (continental, regional, national), and hence makes the application of this approach valid. One drawback with purely bioclimatic models is that they can introduce spatial uncertainties because of (i) interpolation errors, (ii) insufficient station data, and (iii) lack of interpretability of microclimatic signals from standard climate stations which may be biologically relevant to a species' distribution (Guisan and Zimmermann, 2000). Also, bioclimatic envelopes need to be interpreted in the light of the other inter-related factors which affect species distributions, abundance, prevalence and dispersal, including species interactions, disturbance, and other resource factors. Various environmental indicators of habitats, resources and landscape characteristics which influence species distributions can, however, be integrated using higher resolution data sets, which have the potential to improve species distribution models, particularly at more localised scales.

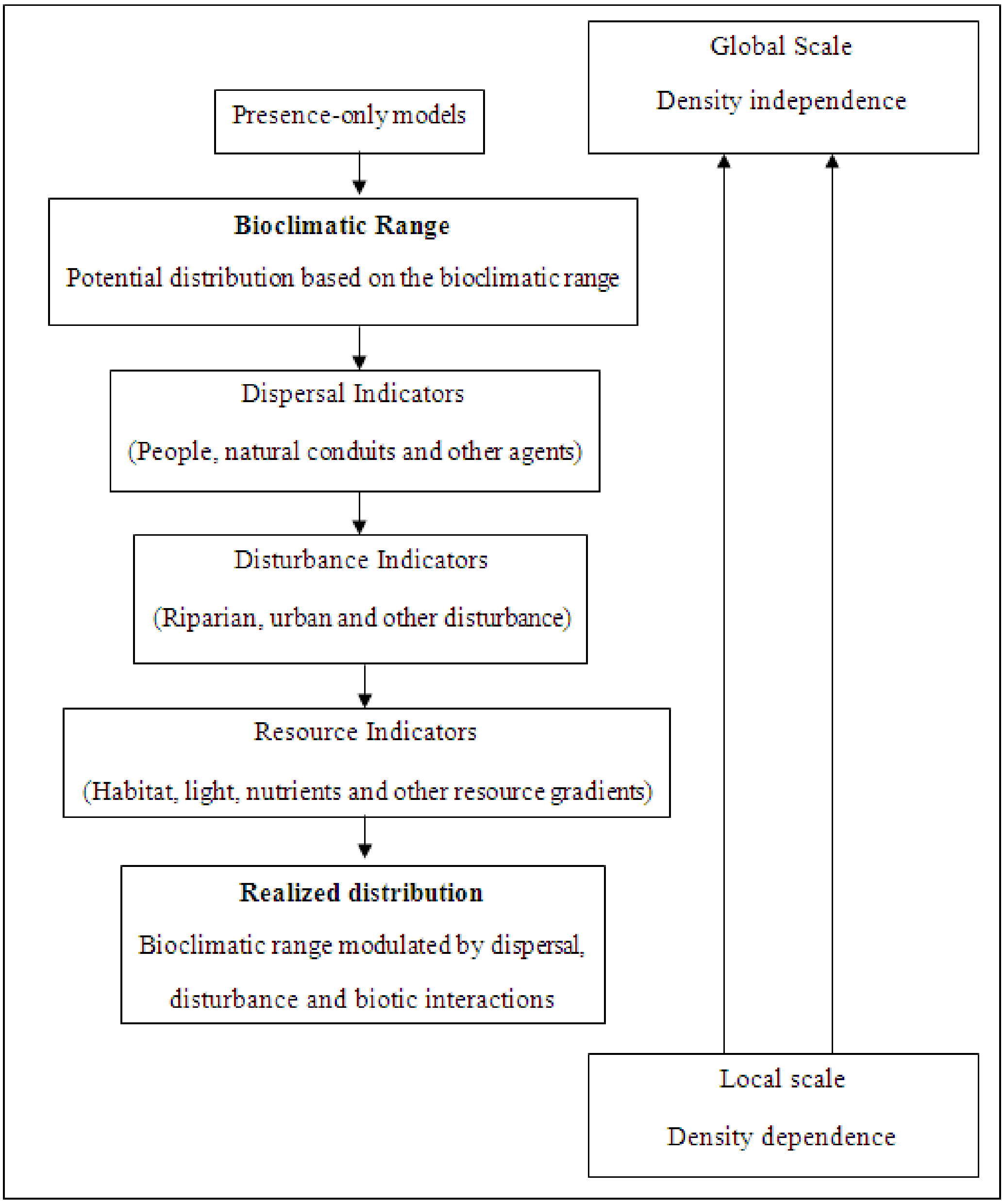

Figure 3.2 A general hierarchical modelling framework for integrating resources, dispersal, disturbance with bioclimatic factors. (Adapted for presence-only models from the 'presence-absence' hierarchy in Guisan and Thuillier, 2005).

Integrating climate change poses new challenges to species distribution modelling. Due to the fact that the future species distributions have not yet been realised, the reliability of niche-based models cannot be taken for granted (Thuiller 2004), and only serve as potential scenarios. To include the effects of climate change, we must be able to either modify the underlying climate data set used for the distribution projection, or else alter the environmental preferences of the derived species (a less satisfactory approach). Climate data sets have been modified using the regional output from the global circulation models or through the adjustment of observed climate by the same magnitude as predicted by Global Climate Models as part of a sensitivity analysis (Kriticos and Randall, 2001; Dirnböeck et al., 2003).

3.3.1 Integrating Climate and Land Use Change in Species Distribution Modelling

Very few assessments integrate potential future land use change scenarios in spatially-explicit species distribution modelling in combination with climate change scenarios (an exception is the published study by Dirnböeck et al., 2003, for the treeline conifer *Pinus mugo*)[24]. There is a growing recognition of the need to integrate future land use changes with climate change in species distribution modelling. Pearson and Dawson (2003) for example, state that accurate projections of future distribution of species will require detailed knowledge of the ability of species to migrate through dynamic heterogeneous (and fragmented) landscapes within the broader constraint of changing bioclimatic envelopes. Table 3.1 illustrates the various Species Distribution Modelling approaches in use that integrate climate change and/or land use change (including habitats, dispersal, disturbance, and other resources) into their modelling frameworks for projecting future species distributions.

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[24] Another example, the HOTSPOTS model, incorporates climate change scenarios and land use. It has the added advantage of being able to predict habitat suitability to spatial resolutions of 100m based on climate and land cover data for New Zealand, and using climatic and habitat exclusion thresholds and optimal values (de Wet et al., 2005 – applied to arboviral disease vectors). However, the land use component is for ‘current’ land use only and so cannot project scenarios into the future.

SDM Type	**Model Examples**	**Approach Used**	**Data Type**	**Integration**		**Study**
				CC	**LUC**	
Bioclimatic envelopes	BIOCLIM (in DIVA-GIS), ANUCLIM SPECIES, and CLIMEX, CLIMATE, CLIMATE ENVELOP	Correlation of species observations and current climate; physiological tolerances	Presence-only	√		Beaumont et al., 2007; Beaumont and Hughes, 2002; Rutherford et al., 1999; Midgley et al., 2002 and 2003; Sutherst, 2003; Kriticos et al., 2003a,b
Factor Analysis	ENFA/ BioMapper	Ecological Niche Factor Analysis – factor analysis	Presence-only	√		Estrada-Pena and Venzal, 2007; Hirzel et al., 2001; Chefaoui and Lobo, 2008 and 2008; Sattler et al., 2007
Generalized Linear Modelling, GLM	BIOMOD	Allows non-linear and non-constant variance; relationship between species distribution and explanatory variables uses a ‘link function’.	Presence-absence			Thuiller, 2003; Guisan et al., 2002
Generalized Additive Modelling, GAM	BIOMOD	Semi-parametric extensions of GLMs; also use ‘link functions to define relationship between response variable and the ‘smoothed’ predictor variables	Presence-only or Presence-absence	√		Araujo et al., 2004 and 2005; Thuiller, 2003; Guisan et al., 2002
Classified and Regression Tree	BIOMOD	Partitions multidimensional space, defined by the	Presence-absence			Thuiller, 2003; Veyssières et al., 2000

analysis, CART		explanatory variables, into homogenous zones, in terms of the response				
Artificial Neural Networks, ANN (and other machine learning techniques)	BIOMOD and GARP	A training algorithm modifies internal parameters/weights, until the predictive success in maximised	Presence-absence			Thuiller, 2003; Manel et al., 1999
Ordinal logistic regression models	Proportional Odds (PO) model, Continuation Ratio (CR) and Stereotype (S) models (Guisan and Harrell, 2000).	Used for semi-quantitative datasets which correspond to species presence-absence (such as percentage cover)	Presence-only	√	√	Dirnböeck et al., 2003

Table 3.1 Examples of species distribution models that integrate either climate change (CC) and/or land use change (LUC).

Given that the distribution data for *Tradescantia* in New Zealand is presence-only, it was decided that the most appropriate species distribution models (from Table 3.1) were presence-only models: BIOCLIM, ENFA, CLIMEX and Generalised Additive Modelling, GAM. Hence, no presence-absence models were used such as: GLM, CART, ANN, or ordinal logistic regression which is based on semi-quantitative presence data (such as percent cover or abundance rankings for a species). Presence-absence models can be run using 'pseudo-absence' data as a substitute for real 'absence' data, as mentioned earlier, however, because *Tradescantia* is such a widespread, invasive species in New Zealand, the reliability of randomly-generated pseudo-absences would be very low, i.e. there would be a high probability of false negatives. The only areas from which reliable 'pseudo-absence' data would be expected are land use types such as 'permanent ice and snow', or 'Afforested pine', and these would be quite self-evident. This ruled out the use of the GAM model, as it would have required generating pseudo-absences in order to run it. The only other model which was suitable is the CLIMEX model (using presence-only data to 'fit' response curves for model calibration). While CLIMEX is very well suited to bioclimatic envelope analysis, access to the software was not as easy as for BioMapper and DIVA-GIS (for the ENFA and BIOCLIM analyses), and so CLIMEX was not used for this study. The other limitation was that land use change scenarios cannot be incorporated in CLIMEX, while they can be in ENFA. BIOCLIM does not integrate land use change scenarios either; however, the advantage of using BIOCLIM over CLIMEX was that BIOCLIM produces habitat suitability/species distribution in terms of probabilities, which are more suitable for providing decision-support to policy-makers. As a result, the following discussion in Sections 3.4 and 3.5 is restricted to BIOCLIM and ENFA – providing the theoretical underpinnings and application to this study for producing the realised species distribution of *Tradescantia* at the national and landscape levels.

3.4 BIOCLIM

BIOCLIM is a bioclimatic prediction system which uses surrogate bioclimatic parameters derived from mean monthly climate estimates to approximate energy and water balances at a given location (Nix 1986). BIOCLIM (as described by Nix, 1986; Busby, 1991) is implemented in DIVA-GIS[25] (Hijmans and Graham, 2006). BIOCLIM uses correlative modelling techniques to interpolate up to 35 climatic parameters for any location where latitude, longitude, and elevation are known. BIOCLIM has been used mainly in the southern hemisphere – Australia, South Africa, South America and New Zealand. However, if climate layers are available it can be applied to any geographic location. BIOCLIM can be used for three main purposes in species distribution modelling:

1) Describing the environment in which the species has been recorded;

2) Identifying other locations where the species may currently reside; and

3) Identifying where the species may occur under different climate scenarios.

BIOCLIM has been used extensively to predict the potential distributions of various target organisms. These organisms include various invasive plant species (Panetta & Mitchell, 1991a,b; Sindel & Michael, 1992), various snakes (Nix, 1986), kangaroos (Skidmore et al., 1996), gliders (Jackson & Claridge, 1999), the helmeted honeyeater (Pearce & Lindenmayer, 1998), the golden-tipped bat (Walton *et al.*, 1992) and Leadbeater’s possum (Lindenmayer *et al.*, 1991).

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[25] DIVA-GIS is a free mapping software that is especially suitable for analysing biodiversity data such as species distributions or other ‘point distributions’. It is currently developed by Robert Hijmans, Luigi Guarino, Andy Jarvis, and Rachel O'Brien. The software is freeware and can be downloaded from the worldwide web at: http://www.diva-gis.org/.

In BIOCLIM, the distribution of a target organism is predicted by characterizing the organism's tolerances in relation to a number of climatic parameters to produce a 'climate profile' for that organism (Busby, 1991). The parameters (predictor variables) are considered to provide a broad characterization of annual variations in temperature and levels of moisture availability (Nix, 1986). BIOCLIM predicts distributions in 'core' and 'marginal' environments using the fuzzy envelope model for the organism under consideration, based on selected threshold values. Nix (1986) defined core environments as those with values falling between the 5th and 95th percentile of each of the predictor variables, and marginal environments as those that fall outside of the core range but within the upper and lower limits of those variables for the species. Nix (1986) points out that these thresholds for core and marginal environments are arbitrary, and they can be estimated using other reasonable values, e.g. Lindenmayer et al., (1991) used the 10th and 90th percentiles to define the core range. The output of BIOCLIM is a distribution map indicating regions of predicted presence (in terms of core and marginal habitat) and regions of predicted absence. Each of these regions is defined by classifying each of the localities in the map region into one of three Boolean or crisp sets (core, marginal or absent) based on the data in the training set. The techniques that use this approach are referred to as crisp envelope models (CEM).

The program interpolates a species bioclimatic envelope, which is a summary of the climate at locations from where the species has been recorded. BIOCLIM is a range-based model that describes a species climatic envelope as a planar rectilinear volume (Figure 3.2); that is, it suggests that a species can tolerate locations where values of all climatic parameters fit within the extreme values determined by the set of known locations (Carpenter et al., 1993). The current potential distribution of a species is identified by interpolating the climate within each grid cell of a Digital Elevation Model (DEM) and comparing it to the climatic profile of the species. Locations with values of all climatic parameters within the range of the species profile are classified by BIOCLIM as climatically suitable. However, multiple levels of classification can be achieved by removing the extreme values of each parameter, and identifying locations with climatic values that lie within different percentile limits. The BIOCLIM process firstly involves ordering each variable. For example, if the climate value for a grid cell falls within the 5th and 95th percentile for each of the variables being considered, the cell is considered to have a suitable climate for the species. This forms a core area for the species. If the cell values for one or more climatic variables fall outside the 90 percentile range but within the (minimum) 0-5th percentile and (maximum) 95-100th percentile, the cell is considered marginal for a species. Cells with values falling outside this total range (for any of the climatic variables) are considered unsuitable for that species (refer to Figure 3.3). Figure 3.4 shows an example of a 5-95 percentile rectilinear envelope. However, it is possible to vary the percentile ranges for the classes on an ad hoc basis; for example the 20th-80th percentile may be considered suitable, and the 0-20th and 80th-100th marginal (Skidmore et al., 1996). The lowest score across environmental values for a grid cell is mapped and can be ‘null’ (outside the observed range of values) or range from near-zero (low) to the theoretical maximum of 50 (very high) (Hijmans and Graham, 2006).

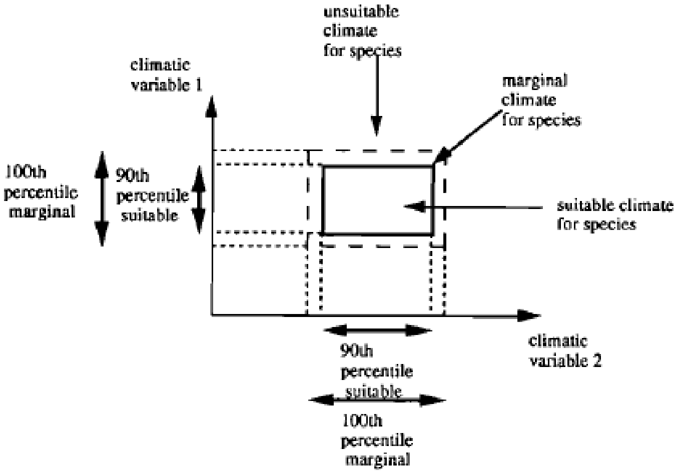

Figure 3.3 Schematic showing 90th and 100th percentiles and how they are used to delineate suitable, marginal and unsuitable climate. (Skidmore et al., 1996, used with permission).

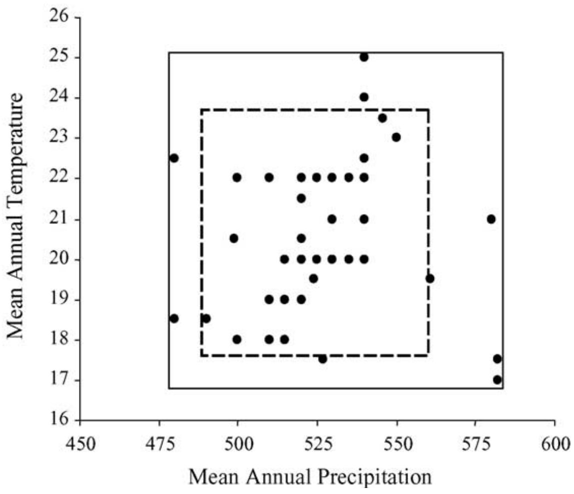

Figure 3.4 The 5-95 percentile used in BIOCLIM. The dots represent values of mean annual temperature and mean annual precipitation at each known location of a hypothetical species. In predicting a species' potential distribution, BIOCLIM would classify all locations with values within the extremes of the species envelope (unbroken line) as suitable. The dashed box represents areas where climatic values outside of the 5–95th percentiles of the species envelope are excluded. This figure has been modified from Carpenter et al. (1993, used with permission).

Within BIOCLIM (v5.1), the user can select which of the climatic parameters to include when identifying suitable habitat. One disadvantage of using less than the full set of 35 parameters is that some possible interactions and partial substitutions between indices may be excluded (Martin, 1996). For example, although an area may have low rainfall, this may be compensated to an extent by lower evaporation, which in turn will depend upon temperature and radiation (Nix, 1986). Therefore, a moisture index was added to later versions of BIOCLIM (Martin, 1996). However, the alternative argument is that, although BIOCLIM can interpolate up to 35 climatic parameters to define a species climatic envelope and to predict its potential distribution, the progressive addition of climatic parameters results in progressively smaller potential distributions. Moreover, Kriticos and Randall (2001) and Chilcott et al. (2003) for example, argue that the inclusion of large numbers of parameters in models such as BIOCLIM may lead to misrepresentations of the potential distribution of species. For example, inclusion of unnecessary parameters may result in areas being classified as climatically unsuitable when in fact the species could occur there (omission errors). This could occur because inclusion of unnecessary parameters may place ecologically unrealistic constraints on identifying climatically suitable habitat. On the other hand, parameters that may in fact limit species distributions can be excluded from the model, and as a result the predicted distributions may have increased commission error rates, i.e. the species is predicted to occur in a given location when in fact it does not. Hence, the number of parameters included in a model is an important consideration because using too few or too many parameters may result in incorrect predicted distributions. Further, the extent to which errors in over- or under-estimating current potential distributions may propagate under models of future climates is unknown. A clear understanding of the relationship between over-fitting and the magnitude of predicted range changes under future climate change scenarios is necessary if predictions from BIOCLIM and other related models are to be useful, credible assessment tools.

3.4.1 Implementing BIOCLIM at the national scale

The climate layers used in the BIOCLIM analysis (and the ENFA analysis presented in Section 3.5.4 of this Chapter) are all a part of the datasets developed through the Land Environments of New Zealand (LENZ) and were used in Chapter 2 as well. Each LENZ climate layer is derived directly or indirectly from mathematical surfaces (thin-plate splines) that use information about the climate, locations and elevation of a number of meteorological stations across New Zealand. Layers for different climate variables are calculated by a process in which the data value for each individual climate station is eliminated in turn and its climate predicted from the stations surrounding it. This process is repeated until a point where there are no further improvements to the fit between the interpolated climate layer and the raw climate data (from the original climate stations) (Leathwick et al., 2002).

The following sections describe the steps taken to develop the baseline species distribution at the national level, based on two LENZ climatic variables: MTminJ-A and AWD. The BIOCLIM Analysis was not undertaken at the landscape level, because it is expected that at this scale, for the given study area, land use and landscape-level factors would play the dominant role associated with *Tradescantia*'s distribution. BIOCLIM is restricted to climatic variables only in its derivation of the ecological niche/habitat suitability of a species. The BIOCLIM analysis was undertaken in several steps:

1) **Data preparation**: A shapefile was created for the 1312 presence observations of *Tradescantia* at the national scale, in ArcMAP 9.1. The underlying attribute table of the shapefile was saved as a text file.
2) **Produced Frequency Graphs:** These graphs provide the frequency of species observations at a particular climate variable value, and are used in calibrating the model for the species ecological niche. Points that are at exactly the same location are included only once. Points that are at a different location but in the same cell of the climate grid are also included once.
3) **Evaluated Outliers:** identifies the outlier species distribution points against each of the climate variables.
4) **Produced Histograms:** The histograms were of MTminJ-A versus AWD (as per the example provided in Figure 3.4). These were used to derive the 50th, 20th, 10th, 5th, and 2.5th percentiles of the two datasets, which would delineate the core, marginal and unsuitable areas for *Tradescantia*. This is helpful to get an idea about the general characteristics of the distribution of these points in ecological space, based on MTminJ-A and AWD (as opposed to the geographical space on the habitat suitability maps produced). (Note: It can also reveal ecological outliers, perhaps caused by incorrect coordinates).
5) **Produced Environmental Envelopes:** The envelopes produced were equivalent to the distribution of the species distribution points in two dimensions of the ecological space. The percentiles were calculated for each variable individually, and then combined. (Note: The percentage of the points that are inside the multidimensional envelope at a certain percentile will be different for each data

set). In this way a link is established between the distributions in ecological and geographic space.

6) **Modelled distributions:** The modelled distribution produced a Habitat Suitability map which classified the suitability into six classes: (1) Excellent: 20-50 percentile, (2) Very High: 10-20 percentile, (3) High: 5-10 percentile, (4) Medium: 2.5-5 percentile, (5) Low: 0-2.5 percentile and (6) Unsuitable.

3.4.2 BIOCLIM results – national level

The bioclimatic envelope for *Tradescantia*, produced by BIOCLIM (see Figure 3.5), represents its realised species distribution at the national scale (refer to Section 3.2.3 for the interpretation of the realised distribution). The broad pattern based on the suitability classes delimits the following:

1) **Excellent suitability:** Parts of Northland, most of the Auckland regions, parts of the Waikato and Eastern Bay of Plenty regions, parts of Taranaki (particularly around New Plymouth and parts of Manawatu and Wairarapa Plains, parts of Gisborne and Hawkes Bay on the North Island. On the South Island excellent suitability occurs in much more constricted coastal areas, primarily along the West and East Coasts as far south as the Haast Pass on the West Coast and intermittently along the East Coast – around the Marlborough Sounds, the Kaikoura coast, Banks Peninsula/Christchurch, and then further south around Dunedin and southern-most parts of Southland, near the Catlins.
2) **High and Very High suitability:** is typically located in areas directly inland from the areas designated as excellent.
3) **Medium and Low suitability:** is given to areas even further inland from the above classes and typically showing the insularity of high elevation, colder sites.
4) **Unsuitable:** areas were rare on the North Island, being restricted to only parts of the Hawkes Bay and the Wairarapa and Manawatu Plains. On the South Island they were furthest inland and typically associated with the coldest montane to alpine areas along the Axial Mountain Ranges.

This habitat suitability distribution derived from BIOCLIM will be further discussed along with the results from the ENFA analysis, in Section 3.6 of this Chapter.

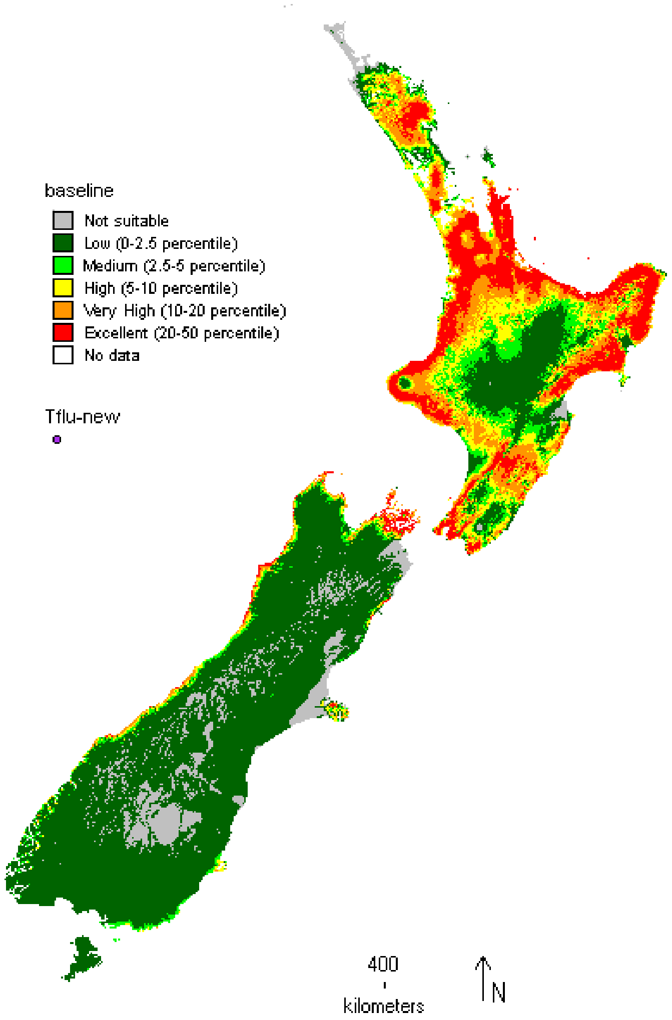

Figure 3.5 The BIOCLIM output of potential species distribution of *Tradescantia fluminensis* based on climatic suitability MTminJ-A and AWD. The major patterns in the distribution show: excellent to very high suitability for most coastal parts of the North Island and the west coast of the South Island (along with the coastal parts around Christchurch, Banks Peninsula and Dunedin). In the north of the North Island, i.e. from Northland to the Auckland and Waikato regions, this maximum suitability extends to 100% of inland areas. High suitability is found further inland (though still within 50km of the coastline on the South Island). Medium to low suitability areas were distinctly located further inland while unsuitable areas were mainly in the inland and alpine

regions of the South Island and the Canterbury Plains. A distinct patch of unsuitable habitat was also located on the North Island in Hawkes Bay.

3.5 Ecological Niche Factor Analysis (ENFA)

The Ecological-Niche Factor Analysis (ENFA) computes suitability functions by comparing the species distribution in the eco-geographical variable (EGV) space with that of the whole set of cells for that eco-geographical variable (Hirzel et al., 2002). It is a relatively new approach designed specifically to circumvent the difficulty with other species modelling techniques of requiring both presence and absence data. It has been applied to the development of habitat suitability models (taken to be equivalent to species distributions), for example: the invasive ring-necked parakeet, *Psittacula krameri* (Strubbe and Matthysen, 2008); the Alpine Ibex, *Capra ibex* (Hirzel et al., 2002); the bearded vulture, *Gypaetus barbatus* (Hirzel and Arlettaz, 2003); the endangered species *Eringium alpinum* (Engler et al., 2004); 43 native New Zealand fern species (Zaniewski et al., 2002); breeding birds in Catalonia, Spain (Brotons et al., 2004) and for a ‘virtual’ species for model testing (Hirzel et al., 2001). This is a multivariate approach which does not require absence data and it builds on Hutchinson’s (1957) concept of the ecological niche of a species. The following sections describe the ENFA method in detail.

3.5.1 Species environmental marginality and specialisation

Sections 3.5.1 and 3.5.2 describe the mechanics of ENFA and the text is based on the article by Hirzel et al., 2002 (pp. 2028 – 2031, used with permission). It is expected that a species will have a non-random distribution with respect to ecological variables, particularly those variables which are physiologically limiting to the species growth and abundance (Hirzel et al., 2002). A non-random distribution could, for example, indicate an optimal range for a species, such that the species is more likely to be located in raster cells that lie within its optimal range. The optimal range may be quantified by comparing the temperature distribution of the cells in which the species was observed with that of the whole set of cells. These distributions may differ with respect to their mean and variances (refer to Figure 3.2).

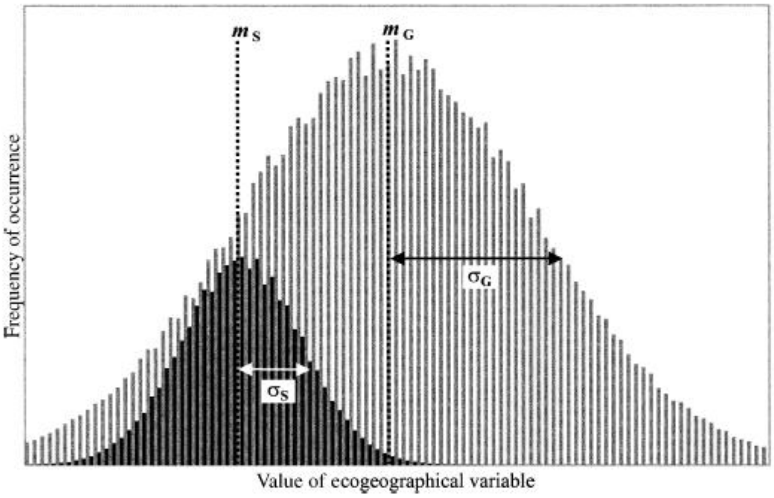

Figure 3.6 The distribution of the focal species on any ecogeographical variable, used in ENFA. The (black bars) may differ from that of the whole set of cells (grey bars) with respect to its mean (*m*S ± *m*G). *m*S ± *m*G defines the "marginality" of the focal species. The distribution of the focal species may also differ with respect to its standard deviation (sS ± sG). sS ± sG defines the "specialization" of the focal species (Hirzel et al., 2002, pg. 2028, used with permission).

The ENFA method is based on the rationale that every species is likely to show some degree of *marginality* (statistically expressed as the difference between the species mean and the global[26] mean for that variable) and some degree of *specialisation* (statistically expressed as the difference between the species variance and the global variance) (see Figure 3.6). The marginality (*M*) of a species is defined as the absolute difference between the global mean (m_G) and species mean (m_S), divided by 1.96 standard deviations (σ_G) of the global distribution as follows:

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[26] 'Global' in this context refers to the whole set of cells within the rasterised dataset for any one variable or set of variables.

$$M = \frac{|\,m_G - m_S\,|}{1.96\,\sigma_G} \qquad \text{Equation (1)}$$

Dividing by σ_G removes any bias introduced by the variance in the global distribution: when the variance of an EGV is larger, a cell selected randomly from that distribution is *a priori* expected to lie further from the mean, according to the size of the variance. The coefficient weighting σ_G (1.96) is used to ensure that the species marginality will almost always lie between zero and one. In particular, if the global distribution for a variable is normal, the marginality of a randomly chosen cell has only a 5% chance of exceeding 1. A large value (close to 1) means that the species occupies a very specialised habitat relative to the global set. Equation (1) explains the principle of the method; the operational definition of marginality implemented in Biomapper™[27] (the software that executes ENFA) is provided by equation (10), which is a multivariate extension of Equation (1) above. Specialisation (*S*) is defined as the ratio of the standard deviation of the global distribution (σ_G) to that of the focal species (σ_S).

$$S = \frac{\sigma_G}{\sigma_S} \qquad \text{Equation (2)}$$

A randomly chosen set of cells from the global distribution is expected to have a specialisation of 1, and therefore any value exceeding unity (i.e. >1) indicates some form of environmental specialisation by the focal species. Specific values for these indices are fully dependent on the global ecogeographical variable set chosen as a reference, such that a species can appear extremely marginal or specialised on the scale of a whole country, but much less so on a subset of it (for instance at the landscape level). Using the marginality and specialisation statistics for a larger set of

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[27] BioMapper is a toolkit of GIS and statistical tools, developed by Alexandre Hirzel (see: http://www2.unil.ch/biomapper/index.html for further information on the software, research publications using ENFA. It is designed to build habitat suitability models and maps for any kind of plant or animal, based on the Ecological Niche Factor Analysis (ENFA). The software is free and can be downloaded at: http://www2.unil.ch/biomapper/products.html.

variables directly leads to Hutchinson's (1957) concept of the ecological niche. Ecological niche is defined as a 'hyper-volume in the multidimensional resource space of ecological variables' within which a species can maintain viable populations, albeit that the fitness levels of those viable populations may not be the same at all locations, due to localised factors (Hutchinson 1957, Austin et al., 1990; Soberón and Peterson, 2005). ENFA uses the ecological niche concept in exactly the same sense, referring to the subset of raster cells in the ecogeographical space where the focal species has a reasonable probability of occurring. This multivariate niche can be quantified on any of its axes by an index of marginality and specialization. A few of the axes will be more meaningful than the rest, and so a factor analysis is introduced.

The reasons for using a factor analysis are twofold. Firstly, ecological variables are rarely independent. As more variables are introduced into the description of a species niche, multi-collinearity and redundancy of variables arise. Hence, one aim of factor analyses is to transform V correlated variables into the same number of uncorrelated factors. As these factors explain the same amount of total variance, subsequent analyses may be restricted to the few important factors (typically, those explaining the largest part of the variance), without losing too much information when removing the less important factors.

Secondly, species specialisation is expected to depend on interactions among several variables. For instance, the temperature one species prefers might vary with humidity. As a result, a species may specialise on a combination of variables, rather than on every variable independently. A factor analysis may allow extraction of the linear combinations of original variables on which the focal species shows most of its marginality and specialization. In ENFA, the first axis is chosen so as to account for all the marginality of the species, and the following axes so as to maximize specialization (Hirzel et al., 2002).

3.5.2 Factor Extraction

ENFA uses raster maps of each of the ecogeographical variables (EGVs), which are grids of *N* isometric cells covering the whole study area. Each cell of a map contains the value of one variable. Ecogeographical maps contain continuous values, measured for each of the *V* descriptive variables. Species maps contain Boolean values (0 or 1), a value of 1 meaning that the presence of the focal species was proved on this cell. A value of zero simply means absence of proof that the species occurs at that location in space, i.e. no verified absence. Each cell is thus associated with a vector in multi-dimensional space whose magnitude and direction are the values of the EGV in the underlying area, and can be represented by a point in the multidimensional space of the EGVs. If distributions for the EGVs are all normal (i.e. multinormal), the combined Scatterplot of all the EGVs in multidimensional space, will have the shape of a hyper-ellipsoid (Figure 3.7).

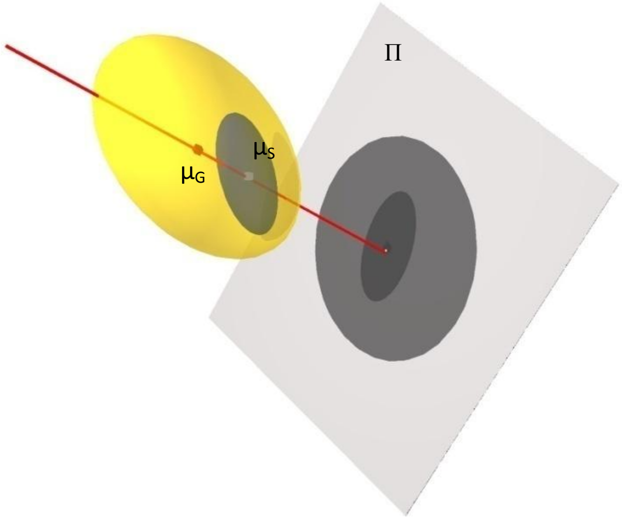

Figure 3.7 Geometrical interpretation of the Ecological-Niche Factor Analysis, ENFA. Cells of the study area are represented in a three-EGV space. The larger, lighter balloon represents the global cloud of cells, while the smaller, darker balloon represents the subset of cells where the focal species was observed. The straight line passing through their centroids (m_G and m_S) is the marginality factor. In order to extract the variance associated with this factor, the cell coordinates are projected on a plane *p* perpendicular to it, thereby producing the two ellipses. Typically, these operations are typically conducted with 20–30 EGVs (Hirzel et al., 2002, pg. 2030, used with permission and

http://biomapper.wikispaces.com/Ecological+Niche+Factor+Analysis, 2009, used with permission).

Figure 3.7 illustrates that the cells where the focal species was observed constitute a subset of the global distribution in EGV space, and are plotted as a smaller hyper-ellipsoid within the global one. The first factor, or marginality factor, is the straight line passing through the centroids of the two ellipsoids. The species marginality, then, is the distance between these two centroids, standardized as in Equation 1 and Figure 3.7, which plots this step for a three-dimensional initial set.

To obtain the specialisation factors, the above reference system of global EGVs (used to derive the marginality factor) is changed in order to transform the *species* ellipsoid into a sphere, the variance of which equals unity (i.e. 1) in each direction. Using this new metric, the first specialisation factor becomes the factor that maximizes the variance of the *global* distribution (while being orthogonal[28] to the marginality factor). The other specialisation factors are then extracted in turn, each step removing one dimension from the space, until all *V* factors are extracted. The specialisation factors are all orthogonal to one another, and hence uncorrelated. Since the factors are sorted by decreasing order of specialisation, the first few (*F*) will thus generally contain most of the relevant information. Their small number and independence make them easier to use than the original EGVs, so that all following operations will be restricted to them. In particular, the suitability of any cell for the focal species (be it classified as 0 or 1 for observation data) will be calculated according to its position in the *F*-dimensional space (Hirzel et al., 2002).

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[28] ‘ Orthogonal’ refers to two planes in space which are at right angles to each other., in this case the marginality factor (plane one) being at a right angle to the first specialization factor (plane two).

3.5.3 National level baseline species distribution

3.5.3.1Implementing ENFA at the national level

a) Preparing the EGV Maps

Each of the data layers were converted into IDRISI32™-formatted maps by importing them into the IDRISI32™ software. The IDRISI maps were then imported into BioMapper as Ecogeographical Variable (EGV) maps. EGV maps were *quantitative* (e.g. MTminJ-A or Deficit), or *Boolean* (binary data, 1 or 0 values only, e.g. species presence).

In BioMapper, the EGV maps were statistically normalised using the Box-Cox function. The consistency and usability of these maps was verified by BioMapper - this operation verified that all the EGV maps had the same background and non-background cells and that there were no constant or near-boolean maps. If there were any such maps, the programme listed the problematic maps.

Before importing the species distribution points map into BioMapper, it was converted from an ArcGIS vector shapefile to an IDRISI point file using the Pointras command. The *species presence* map was added in the Work Maps and marked as “Species map”.

b) Ecological Niche Factor Analysis (ENFA)

ENFA was performed to produce the scores matrix, which contains the contribution of each EGV to each factor. In this way it was possible to attribute the contribution of each EGV to the marginality factor (Factor 1) and to the specialisation factors (Factor 2 to Factor *n*, where *n* denotes the total number of factors). The coefficients gave a weight to each EGV map, and were also used to compute the Habitat Suitability map. These associated marginality and specialisation outputs were examined with respect to the species ecology of *Tradescantia* in Chapter 2. This produced the Ecological Niche Model.

The steps taken were as follows:

1) The *covariance matrix* was computed
2) An Ecological Niche Factor Analysis (ENFA) was performed. The scores of this analysis (the eigenvectors) were saved automatically.
3) The eigenvalues were checked (values had to be ≥ 0).

c) Habitat Suitability Computation

Finally, the Ecological Niche Model (computed in the step above), was used to compute a *Habitat Suitability Map*. The followed steps were followed:

1) The Habitat Suitability Map was computed using the 'Extreme Optimum Medians algorithm' (also known as the Veronika algorithm) because it was able to derive species habitat suitability maps for species which exhibit optimal suitability on one of multiple EGVs at the extreme high or low values of the EGVs (Braunisch, 2008). This is the latest algorithm to be added to the suite of algorithm options[29] in Biomapper, and is particularly suitable for a species like *Tradescantia*.
2) The factor maps to be used in the habitat suitability computation were selected. By default, the weight assigned to each factor was computed from the eigenvalues.

See Figures 3.8 and 3.9 which show evidence of the extreme optimum of the national level species distribution of Tradescantia with respect to the EGVs MTminJ-A and AWD. Both Graphs were produced using the Box-Cox transformed MTminJ-A and AWD. Therefore, they are the normalised version of the raw EGVs.

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[29] Other algorithms include the Medians, Distance geometric mean, Distance harmonic and Minimum distance algorithms.

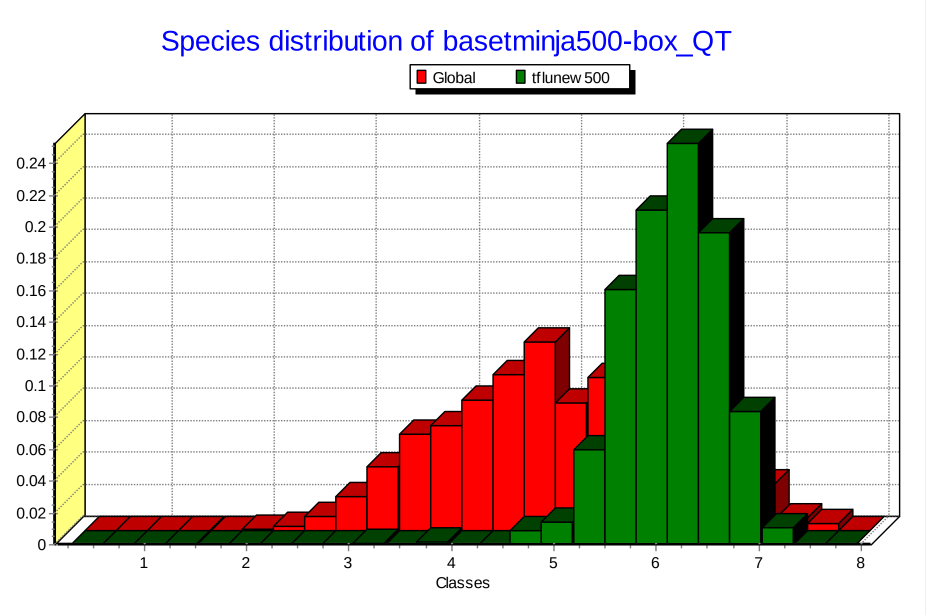

Figure 3.8 Bar Graph of the global distribution of Box-Cox transformed MTminJ-A at the national level (red bars), and the species distribution of *Tradescantia* (green bars). The MTminJ-A shows a left-skewed normal distribution both for the global distribution of MTminJ-A and the species distribution, with the optimum species range tending towards the higher to extreme high values of MTminJ-A.[30]

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[30] Note: The font sizes in the red/green bar graphs in the remaining Sections of this Chapter could not be enlarged, as BioMapper produces only one font size.

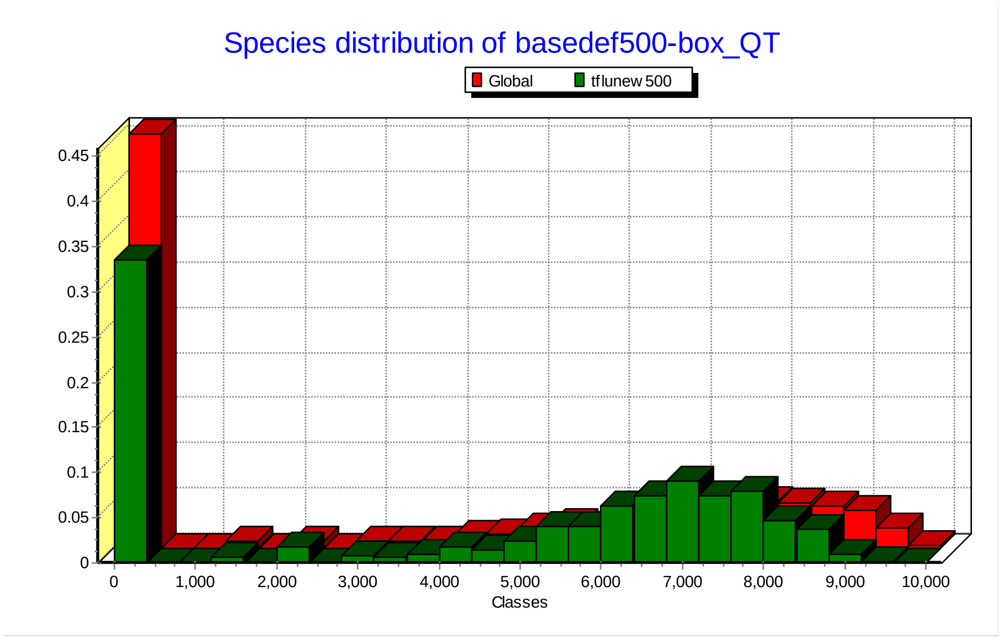

Figure 3.9 Bar Graph of the global distribution of Box-Cox transformed AWD at the national level (red bars), and the species distribution of *Tradescantia* (green bars). A distinct species extreme optimum at AWD=0 is evident, which is why the Extreme Optimum Median algorithm was used. Although the Box-Cox Transformation did not fully normalise the AWD EGV, this did not affect the ENFA computations, as empirically it has been found that normality of the data is not a crucial factor and that the modelling can still be performed well without Box-Cox transforming the data (Alexandre Hirzel, http://www2.unil.ch/biomapper/faq-bak.html#BoxCox).

At the national level, two baseline models were generated: Baseline1 at a 100m x100m spatial resolution and Baseline2 at a 500m x 500m resolution. The underlying LENZ climate data were available at a resolution of 100m x 100m for MTminJ-A and Annual Water Deficit, which is why the Baseline1 model was generated. However, it was found that at such a high resolution extrapolation was not possible, using even a 2GB RAM computer. Therefore, the climate layers were re-sampled to a resolution of 100m x 100m and the model Baseline2 was generated.

d) Habitat Suitability Model Evaluation

The predictive power of the habitat suitability (HS) map was evaluated by a cross-validation process. This computed a confidence interval for the predictive accuracy of the HS model. The species locations were randomly partitioned into *k* mutually exclusive but identically-sized sets. The Huberty's rule[31] was used to select the number of *k*-partitions to use in partitioning the validation and calibration datasets from the original dataset of *Tradescantia* presence. *k*-1 partitions were used to compute the HS model and the left-out partition was used to validate the HS model on independent data. This process was repeated *k* times, each time by leaving out a different partition. This process resulted in *k* variations of HS maps. This produced the Continuous Boyce Index (CBI). See Figure 3. 10 which shows the theoretical ideal graph of the Continuous Boyce Index (Hirzel et al., 2006), on which the validations are based. This is also the graph used to reclassify the Habitat Suitability Map on the basis of: optimal, suitable, marginal and unsuitable habitats. 'Optimal' areas have the highest P/E ratio because the number of cells predicted as suitable is much higher than the expected number of cells, if the distribution was random. Similarly 'Suitable' areas also have a high P/E ratio, though with a lower slope, indicating that fewer cells are predicted as suitable compared to the 'optimal' than expected, if the distribution was random. 'Marginal' areas have a much lower P/E ratio, however, because they are still slightly above the random line, they are predicting slightly more cells as suitable than would be expected if the distribution was random. 'Unsuitable' areas fall below the random line, indicating a low P/E ration, such that the number of cells predicted as suitable is less than that expected if the distribution was random, and therefore is considered unsuitable for the species. The line at 1 represents a totally random model. By comparing these maps and how they vary amongst each other, it was possible to assess their predictive power. An

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[31] The Huberty's rule is a rule of thumb for determining the ratio of calibration and validation points. It suggests that this ratio should be 1/(1 + sqrt(V - 1)), where V is the number of EGVs. (p. 40 in Fielding, A.H. & Bell, J.F. (1997)).

area-adjusted frequency cross validation was undertaken. Section 3.5.4.2 presents the results of the national level ENFA analysis.

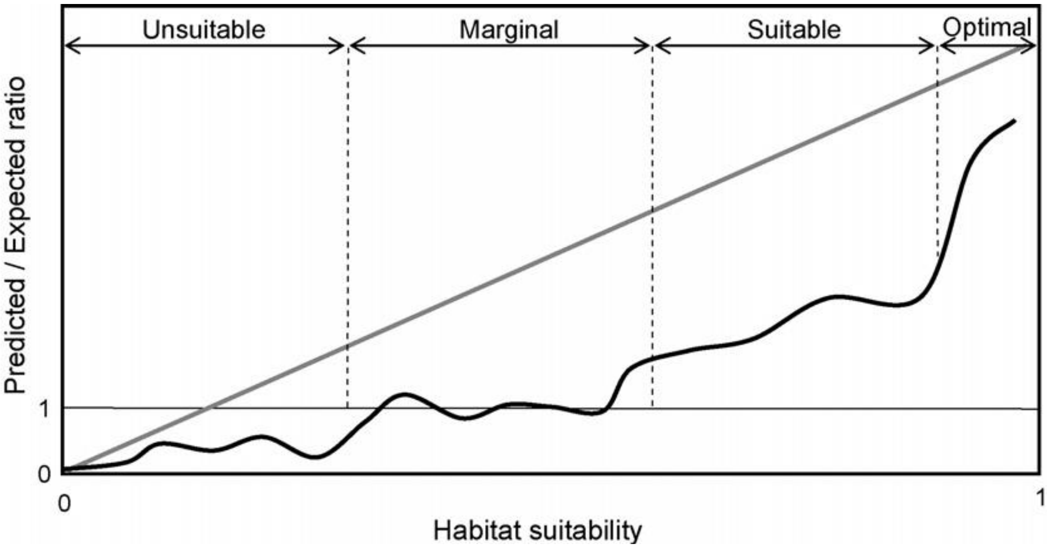

Figure 3.10 Predicted suitability/Expected suitability (P/E) curve shapes. (Source: Hirzel et al., 2006, pg. 150, used with permission). The ideal model produces a straight line (dark grey) while actual models tend to show more irregular curves (black solid line). The shape of the curve can be used to delineate the boundaries of the habitat suitability classes (dashed lines). Note that in this graph the HS classes are given values between 0-1; however ENFA produced CBI graphs that have the x-axis between 0-100, to match the suitability classes produced in the Habitat Suitability Maps; however, they are still comparable.

3.5.3.2 ENFA results – national level

Figures 3.11 is the Habitat Suitability Map of *Tradescantia*'s distribution produced as the output of the ENFA. This map was then re-classed, using the Continuous Boyce Index (CBI) as a *guide* only (described in Figure 3.10) into Core, Marginal and Unsuitable Habitats. The *actual* cut-off values for each of the classes were taken from Hirzel et al., (2002) which suggests using the following values for reclassification, where HS=Habitat Suitability value: (1) HS≥50 for Core areas; (2) 10≤ HS ≤ 50 for Marginal areas and (3) HS≤10 for Unsuitable areas. The result of this reclassification is shown in Figure 3.12. The 'unsuitable' classes are delineated from about HS=10, given that no presences are recorded below that value. The plateau-like region found between HS values 15-70, indicates the marginal areas, while HS>70 indicates that the model is predicting the most presences in these classes than would be expected by chance. Figure 3.11 and 3.12 show some of the following key features at the national scale:

1) **Core Areas:** on the North Island are situated in parts of Northland, most of the Auckland region, Waikato, Bay of Plenty, along the coastal regions of the east and west coast to New Plymouth and Gisborne, Hawkes Bay, coastal parts of the Wellington region and Wairarapa. On the South Island highest suitability classes are situated around the Marlborough Sounds in coastal areas.
2) **Marginal Areas:** these are mainly situated around parts of the Waikato, Manawatu, Wairarapa regions and in a few parts of the South Island, for example inland to Nelson, parts of the West Coast, Christchurch, and Dunedin, i.e. adjacent to Core areas.
3) **Unsuitable Areas:** on the North Island are located in the northern-most tip of Northland, the Central Plateau, parts of Hawkes Bay and the Wairarapa Plains; and on the South Island most areas apart from the coastal areas of the east and west coast.

The national habitat suitability (Baseline) for *Tradescantia* will be discussed further in Section 3.6. Tables 3.2 and 3.3 show various model statistics which were used to select the model used to produce the Habitat Suitability Map at the national level. Both Baseline1 and Baseline2 had a high model quality, measured by the Continuous Boyce Index values (CBI) of 0.9 and 0.86. While the CBI was slightly higher for Baseline1, the standard deviation was also higher (0.2, compared to 0.05 for Baseline2), indicating that the overall model quality was slightly better for Baseline2. Table 3.3 shows that in both models, the marginality factor accounted for 81% of the total model information, due mainly to MTminJ-A; and only one specialisation factor in each model accounted for the remaining 19% of the information, due mainly to AWD.

Model: scale	**#Factors**	**ExS**	**ExI**	**HS**	**BI**	**CBI**	**SD**	**F**
Baseline1:100m	2	1.0	1.0	Mve	0.9	0.91	0.05	7
Baseline2:500m	2	1.0	1.0	Mve	1.0	0.86	0.05	>6

Table 3.2 National level Baseline model statistics. Both models performed very well, based on their CBI values which will be discussed in Section 3.5.4.3. ExS=Explained Specialisation; ExI=Explained Information; HS=Habitat Suitability algorithm – Mve (Extreme Optimum Medians); BI=Boyce Index; CBI=Continuous Boyce Index; SD= Standard Deviation; and F=*F*-value. Baseline 2 was selected, given that it could be produce at a slightly larger spatial resolution which improved the model extrapolation using the future scenarios in Chapter 6.

EGVs per Model	**EGV Contributions to Factors**	
Baseline1:100m	**Marginality (81%)**	**Spec. 1 (19%)**
MTminJ-A	++++++++++	**
AWD	++	**********
Baseline:500m	**Marginality (81%)**	**Spec. 1 (19%)**
MTminJ-A	++++++++++	*
AWD	+	**********

Table 3.3 EGV contributions to the two factors derived by ENFA at the national level. MTminJ-A contributes to 81% of the species marginality, while AWD 19%. Marginality in this context would be described, as the broad climatic suitability. Specialisation at the level, is less meaningful, as to discriminate specialisation, would require more variables, for instance, Land cover/ Land use, which is not used in this analysis. The plusses represent marginality and the stars specialisation – the number of each a qualitative indicator of the EGV contribution to respective factors.

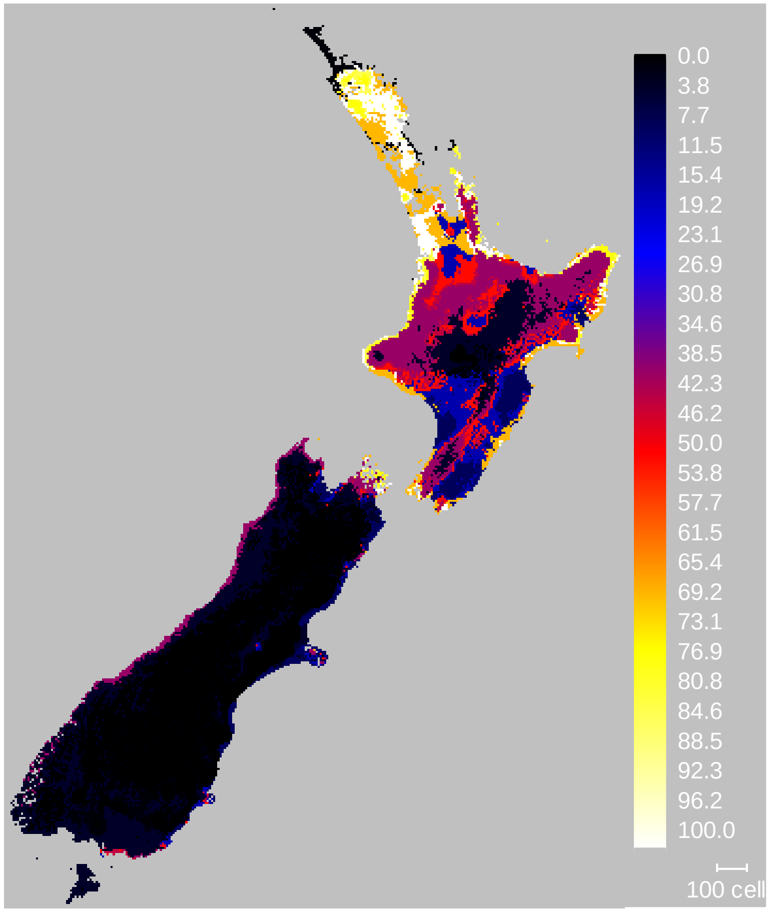

Figure 3.11 Baseline habitat suitability map produced by ENFA combining MTminJ-A and AWD.

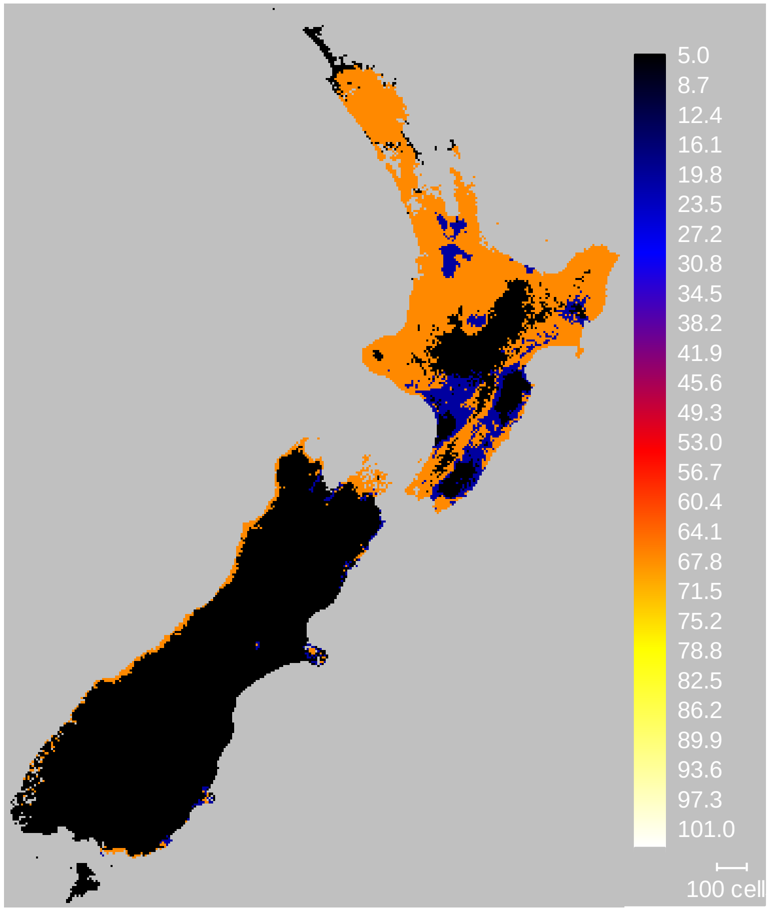

Figure 3.12 The reclassified baseline distribution: core (orange), marginal (blue) and unsuitable (black) areas.

3.5.3.3 Validation of the ENFA/BioMapper model results

The high Continuous Boyce Index (CBI) value (as explained earlier), and its associated low standard deviation, indicates a very good model was produced using the two EGVs MTminJ-A and AWD. The CBI graph (Figure 3.13) shows the ratio of the number of predicted suitable cells to the number expected suitable cells for each habitat suitability class (Predicted/Expected Ratio). The narrowness of the 90% confidence interval (dashed lines) around the median line (black plain curve) reflects the robustness of the model along the habitat suitability (HS) classes from 0-100. This model was quite robust along the full range, though the variance increased slightly towards the upper end for HS classes >75. This indicates that the model is slightly less robust for the very high suitability classes than it is for the marginal or unsuitable classes.

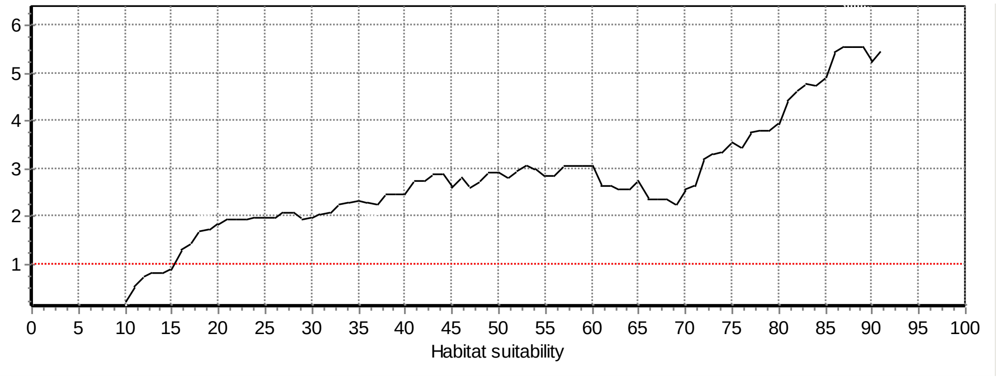

Figure 3.13 The national level Baseline 2 P/E ratio per Habitat Suitability class. Where the P/E ratio is <1 this indicates where the model predicts less presence of *Tradescantia* than expected by chance. Hence, the 'unsuitable' classes are delineated from about Habitat Suitability (HS)=10-15, given that no presences are recorded below HS=10. The plateau-like region where 15≤HS≤70, indicates marginal areas, while HS>70, optimal areas. The solid line indicates the 'median' of the *k*-partition validation model runs. In this case k=2 based on Huberty's rule. The dashed lines are the 95% confidence intervals. The tight fit of the 95% confidence interval lines around the median slid line, indicates that the model is robust in predicting all the Habitat Suitability classes (Hirzel et al., 2006).

From these results it can be said that ENFA/Biomapper models the distribution of *Tradescantia* very well using MTminJ-A and AWD. Therefore, at the national level a very good baseline distribution model was developed for *Tradescantia*, on the basis of which the extrapolation models are produced in Chapter 6. The next section models the distribution of *Tradescantia* at the landscape level, incorporating, habitat (land use) and disturbance-related variables.

The model Baseline2 was also used to extrapolate to the future in Chapter 6, using the scenarios from Chapters 4 and 5 and therefore, will be discussed further in Chapter 6.

3.5.4 Landscape-level baseline species distribution

3.5.4.1Implementing ENFA at the landscape level

The same procedures were followed as for the ENFA analysis described in Section 3.4.3.1 for the national-level analysis. The main differences were the set of EGV spatial maps used, the spatial resolution of the maps, and the species presence data set used for the analysis at the landscape-level. Also, the riparian layer was made boolean; so that each individual class in the riparian layer became a new layer with a value of 0 or 1 (1 being cells where that class was present and 0 where it was absent). The boolean layers were then converted into quantitative layers using the ‘Circan’ module of Biomapper. This conversion involved calculating the ‘Frequency of occurrence %’ for each layer: the output layer showed the frequency of occurrence of patches of cells within a radius of 5 cells (at a spatial resolution of 15m x 15m). ENFA required the boolean layers to be converted in this way. This produced eight new layers, though only four of these were relevant to the analysis: (1) Herbaceous non-riparian (2) Riparian woody and (3) Woody non-riparian (4) Herbaceous riparian.

Several baseline models were generated, using the ‘Extreme Optimum Median’ algorithm (also known as the ‘Veronika’ algorithm) Biomapper (Braunisch et al., 2008), by selecting different combination of EGVs to test the change to model quality produced. The models were generated at two separate spatial resolutions (15m x 15m and 50m x 50m). The 15m x 15m models could not be extrapolated using the future scenario variables as ENFA required more RAM than was available on a 2GB computer. Therefore the 50 x 50m models were generated. The best model was selected to create the landscape-level Habitat Suitability model and HS Map for *Tradescantia* and to produce the extrapolation model for generating the future scenarios at the landscape level. The baseline HS Map was used to compare the spatial changes against the future extrapolated scenarios. These were a measure of the change in the species distribution of *Tradescantia*. The EGV maps used to model the landscape-level distribution of *Tradescantia* in Biomapper (using ENFA), are provided in Table 3.4.

Data Source	**Variable**	**Scale**	**Resolution**
LENZ	MTminJ-A	National	100m, 50m and 15m
LCDBII	Urban Class		100m
	Proximity to Urban	National	50m and 15m
ECOSAT Riparian: Environment Bay of Plenty		Regional, landscape	15m
Environment Bay of Plenty	Roads	landscape	linear
	Proximity to Roads	landscape	50m and 15m
Environment Bay of Plenty	Stream network	Regional, landscape	linear
	Proximity to Streams	Regional, landscape	50m and 15m

Table 3.4 Species-environment datasets for landscape level modelling. The MTminJ-A was re-interpolated to 15m using a grid of points spaced at 15m over the 100m LENZ MTminJ-A layer. Proximity to Urban, Proximity to roads and Proximity to Streams were all derived at a 15m spatial resolution using the 'Euclidean distance' function in ArcGIS 9.0, and then also re-sampled at a resolution of 50m.

3.5.4.2 ENFA results – landscape level

Figures 3.14-3.19 show the frequency of *Tradescantia* against each of the frequency classes for the global distribution of each EGV, generated by Biomapper. The main pattern of interest is that *Tradescantia* has higher frequencies of occurrence in the more extreme classes (higher MTminJ-A) and at lower or zero Proximity to Urban, Proximity to Roads and Proximity to Streams. The riparian layer showed that *Tradescantia* was most frequently found in the following classes: 3-Woody non riparian vegetation, 4-Herbaceous non-riparian vegetation, 6-Riparian woody vegetation and 7-Herbaceous riparian vegetation. These patterns were discussed in Chapter 2, Section 2.5, and are provided here simply to show their relationship to the global (or landscape level) distribution of each of the EGVs as generated by Biomapper.

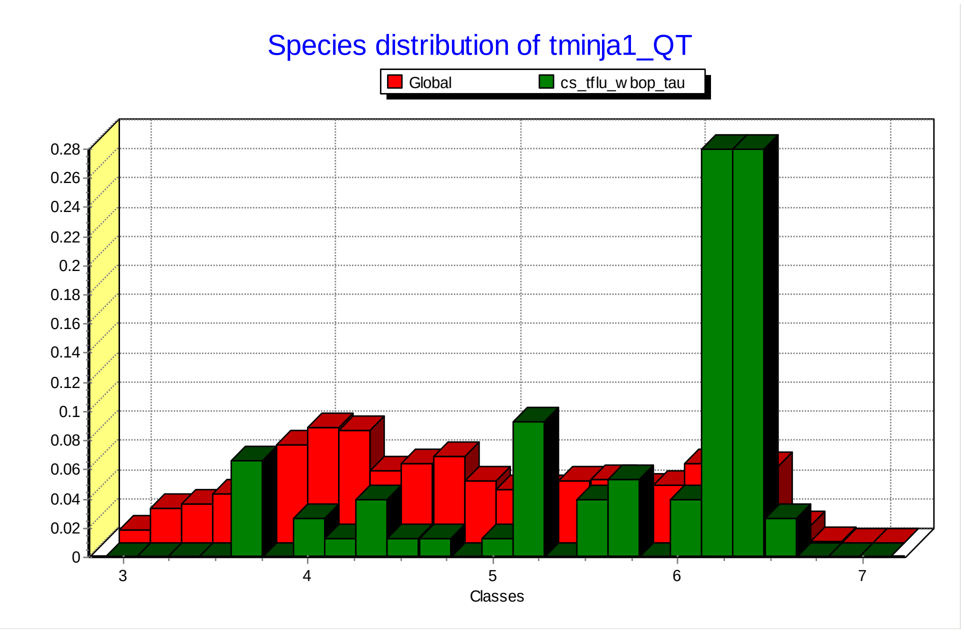

Figure 3.14 The global distribution of MTminJ-A (red bars), and the species distribution of *Tradescantia* (green bars). This indicates an extreme optimum between 6.0-6.5^{o}C. The distribution is strongly left-skewed, which also highlights the extreme optimum.

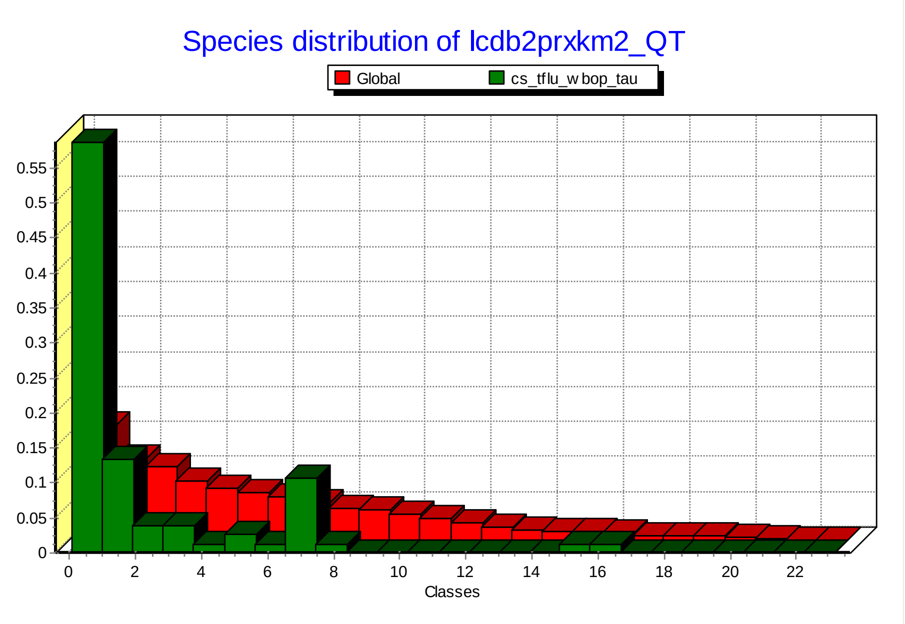

Figure 3.15 The global distribution of Proximity to Urban (LCDBII) (red bars), and the species distribution of *Tradescantia* (green bars). This indicates an extreme optimum closer to Proximity=0. The distribution is strongly right-skewed.

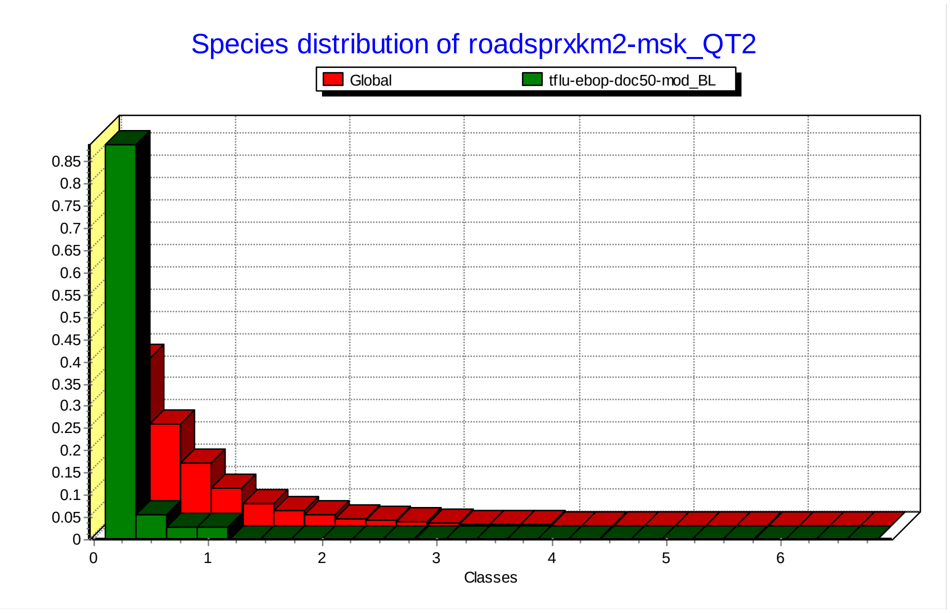

Figure 3.16 The global distribution of Proximity to Roads (red bars), and the species distribution of *Tradescantia* (green bars). This also indicates an extreme optimum closer to Proximity=0. The distribution is strongly right-skewed.

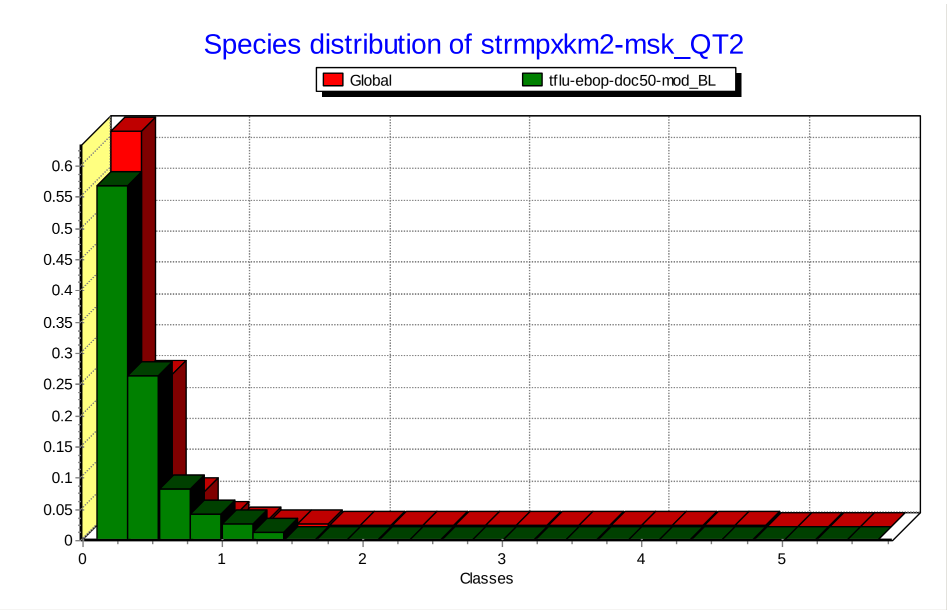

Figure 3.17 The global distribution of Proximity to Streams (red bars), and the species distribution of *Tradescantia* (green bars). This also indicates an extreme optimum closer to Proximity=0. The distribution is strongly right-skewed.

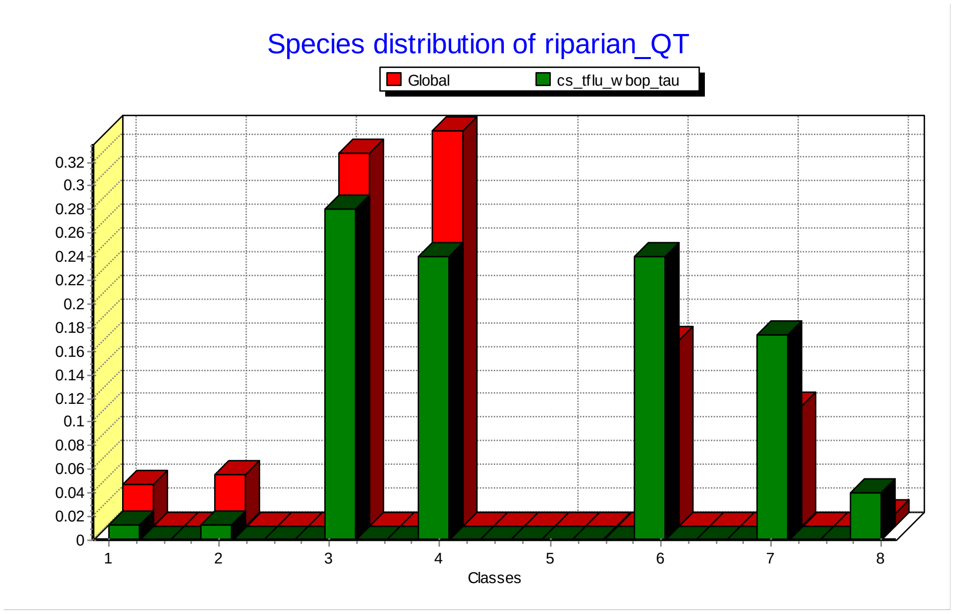

Figure 3.18 The global distribution of Riparian classes 1-8 (red bars), and the species distribution of *Tradescantia* (green bars). Class1=Water; Class2=Bare Ground; Class3=Woody non-riparian vegetation; Class4=Herbaceous non-riparian vegetation; Class5=Streambed; Class6=Riparian woody vegetation; Class7=Riparian herbaceous vegetation and Class8=Riparian bare ground. Classes 3, 4, 5 and 6 were optimal habitat for *Tradescantia*.

Figure 3.19 is the correlation tree based on the global values of each of the eight EGVs used in various combinations in the baseline models. It shows that the EGVs Proximity to Urban and MTminJ-A are quite strongly correlated (correlation coefficient = 0.697). In Biomapper, highly correlated variables can be retained or removed from the model, as they do not change the information explained by each factor significantly. In this case, because the correlation coefficients were not very high, it was decided that both MTminJ-A and Proximity to Urban would be retained in each baseline model (in addition to any other variables that were added to them). This was because these two EGVs were the main variables describing both baseline climate and land use, which was part of the central question addressed by this thesis. They were also the main variables of importance in the future scenarios developed in Chapters 4 and 5.

Six different baseline models were developed to select the best model for producing the baseline HS model and Map and the future extrapolation models. Table 3.5 shows the results of the model quality statistics generated by Biomapper for models at a 15m x 15m spatial resolution (Baslines1-3) and at a 50m x 50m spatial resolution (Baselines4-6). The highest model qualities were produced for Baselines1, 4 and 5 with Continuous Boyce Index (CBI) values of 0.92, 0.87 and 0.89 respectively and low SD values. All of the models either explained all of the spatial distribution and specialisation (ExS and ExI both =1.0) or else exhibited reasonably high values of both. This means that both the marginality and specialisation of *Tradescantia* was explained very well by all models, but they were highest for Baselines 1, 4 and 6.

Model: scale	EGVs	Factors	ExS	ExI	BI	CBI	SD	F
Baseline 1:15m	1-3	3	1.0	1.0	1	0.92	0.06	13
Baseline 2:15m	1-4	3	0.933	0.967	1	0.68	0.20	17
Baseline 3:15m	1-8	5	0.850	0.925	1	0.76	0.25	40
Baseline 4:50m	1-3	3	1.0	1.0	1	0.87	0.05	15
Baseline 5:50m	1-4	3	0.745	0.873	1	0.89	0.09	22
Baseline 6:50m	2-4	3	1.0	1.0	0.75	0.64	0.24	>6

Table 3.5 Model quality comparisons for the six Baseline models generated using ENFA, at the landscape level. ExS=Explained Specialisation; ExI=Explained Information; HS=Habitat Suitability algorithm – Mve (Extreme Optimum Median); BI=Boyce Index; CBI=Continuous Boyce Index; SD= Standard Deviation; and F=F-value. The EGVs used per model are described below the table. EGVs used: 1-MTminJ-A, 2-Proximity to urban, 3-Proximity to streams, 4- Proximity to roads, 5- Frequency of Riparian woody vegetation %, 6- Frequency of Woody non-riparian vegetation %, 7- Frequency of Herbaceous non-riparian vegetation %, and 8- Frequency of Riparian herbaceous vegetation %.

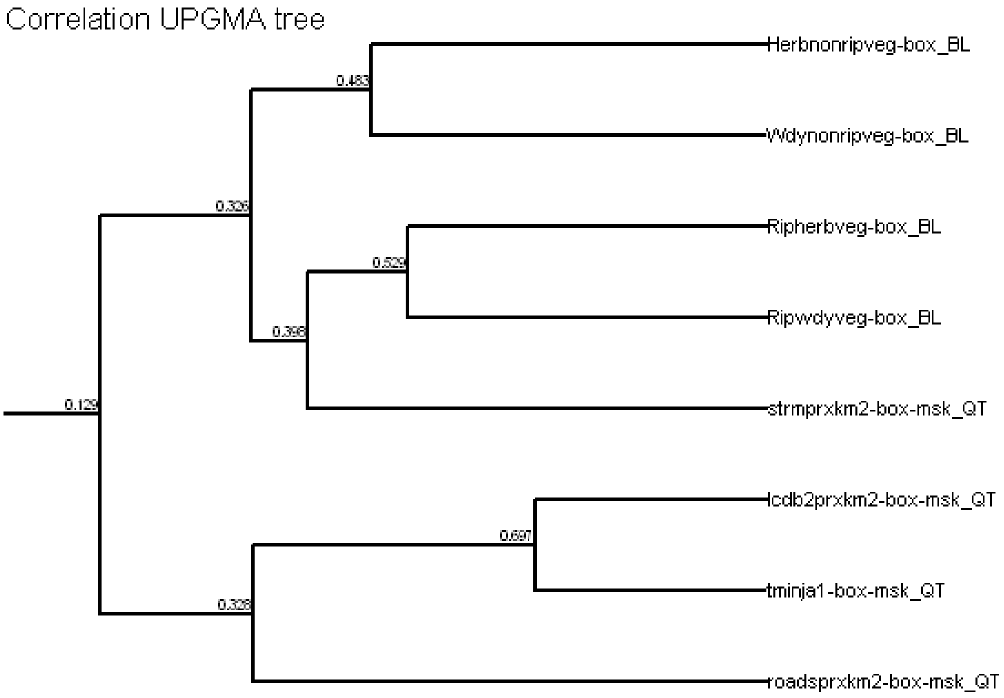

Figure 3.19 The Global Correlation Tree for the eight landscape level EVGs, used in ENFA. Proximity to Urban (lcdb2prxkm2-box-msk_QT) and MTminJ-A (tminja1-box-msk_QT) had the highest correlation (0.697), followed by Riparian herbaceous vegetation (Ripherbveg-box_BL) and Riparian woody vegetation (Ripwdyveg-box_BL) (0.529). None of the other variables were significantly correlated. The other EGVs shown are: Herbaceous non-riparian (herbnonripveg-box_BL), Woody non-riparian vegetation (Wdynonripveg-box_BL), Proximity to Streams (strmprxkm2-box-msk_QT), and Proximity to Roads (roadsprxkm2-box-msk_QT).

Table 3.6 shows contributions by each of the EGVs to each of the main factors generated by ENFA. The first factor is the marginality factor, while the subsequent factors are the highest specialisation factors for each model. MTminJ-A, Proximity to urban and Proximity to roads were the EGVs which contributed strongly to the marginality Factor. Baseline 3 shows that at a 15m x 15m resolution Herbaceous non-riparian, Riparian woody vegetation and Woody non-riparian vegetation (along with MTminJ-A) were the EGVs which contributed most strongly to the all of the specialisation factors. All the other models produced Habitat Suitability maps which described the marginality better than the specialisation, because the riparian/non-riparian EGVs were excluded. As a result Baselines 1, 2, 4, 5, and 6 showed the broad suitability for *Tradescantia*, while Baseline 3 was the only model which was able to discriminate the higher resolution specialisation of *Tradescantia*'s niche within riparian and non-riparian habitats at the landscape level.

EGVs per Model	**EGV Contributions to Factors**				
Baseline 1:15m	**Marginality (23%)**	**Spec. 1 (49%)**	**Spec. 2 (27%)**		
Proximity to urban	--------	******	0		
Proximity to streams	0	0	**********		
MTminJ-A	++++++	********	0		
Baseline 3:15m	**Marginality (16%)**	**Spec. 1 (29%)**	**Spec. 2 (19%)**	**Spec. 3 (12%)**	**Spec. 4 (10%)**
Herbaceous non-riparian veg	-	******	*	*********	****
Proximity to urban	------	*	******	0	*
Riparian herbaceous veg	+	0	*	*	*
Riparian woody veg	++	******	0	*	****
Proximity to roads	------	0	0	*	0
Proximity to streams	0	0	0	0	*******
MTminJ-A	+++++	0	********	0	*
Woody non-riparian veg	0	******	*	****	***

Baseline 4:50m	**Marginality (17%)**	**Spec. 1 (53%)**	**Spec. 2 (30%)**		
Proximity to urban	------	*****	********		
Proximity to streams	-	********	***		
MTminJ-A	++++++++	****	******		

Table 3.6 The contribution of each of the EGVs to the marginality and specialisation factors in the six baseline models. (+) or (-) indicate where an EGV has a positive or negative relationship with the marginality factor respectively, and the number of (+)s or (-)s indicates the strength of the relationship. (*) indicates a positive relationship of an EGV with the specialisation factors and the number of (+)s indicating the strength of this relationship. (0) indicates the where there is no contribution by an EGV to a particular factor.

Figures 3.20-3.24 show the P/E curves for each of the Baseline1-6 models. The two models which show exception to the general exponential curve trends of the others are Baselines 2 and 6. A good baseline model, therefore, would be either Baseline 1, 3, 4 or 5. Since extrapolations were not feasible at the 15m x 15m scale, Baselines 1 and 3 were eliminated. Baseline 4 explained more of the marginality and specialisation than Baseline 5, therefore, Baseline 4 was selected as the best model for the purpose of generating the Baseline Habitat Suitability Model and Map and for producing the extrapolation models.

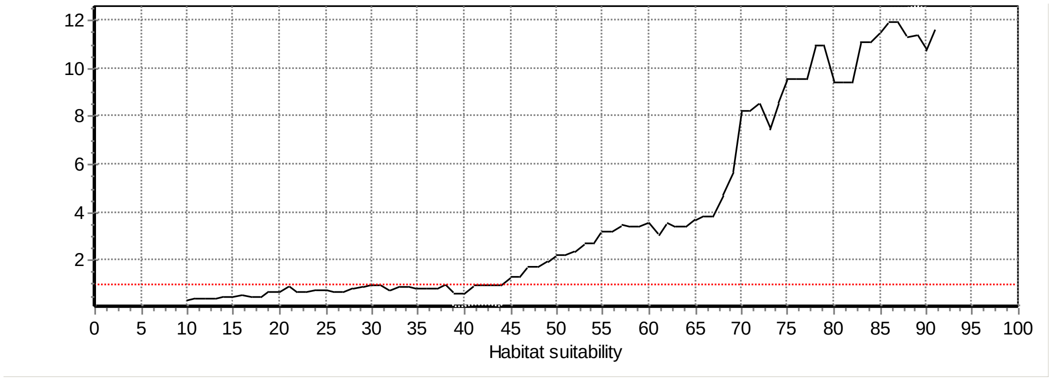

Figure 3.20 Baseline1 P/E ratio curve. Shows a good model, in that the curve shape is similar to the ideal graph shown in Figure 3.10 for the Continuous Boyce Index, with a steadily increasing P/E to the higher optimal classes. However, one drawback is that the 'optimal' values between HS=70-95 shows rather erratic 95% confidence intervals (dashed lines), which indicates that this model is slightly less very robust in predicting the higher/optimal HS classes.

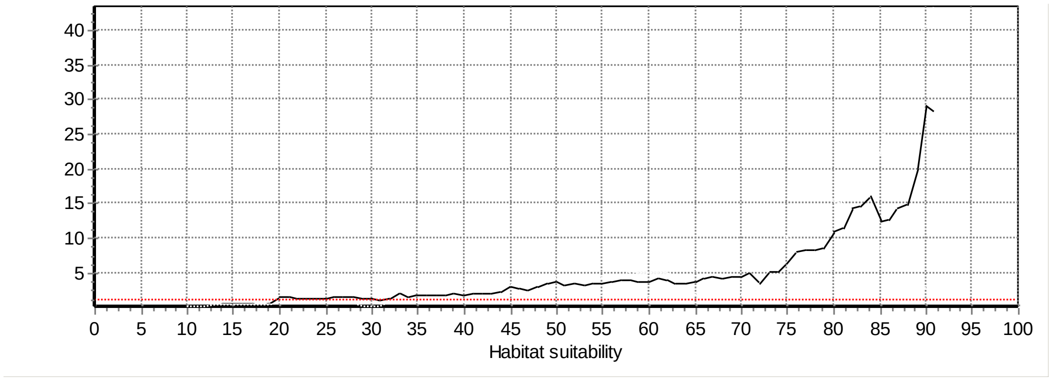

Figure 3.21 Baseline3 P/E ratio curve. Shows a weak curve, with almost all HS classes <70 having very low P/E values, followed by a peak between HS=85-90. The 95% confidence interval around the median is very wide between HS=85-90, indicating the prediction of the higher HS classes will not be very robust and therefore, this model was not selected.

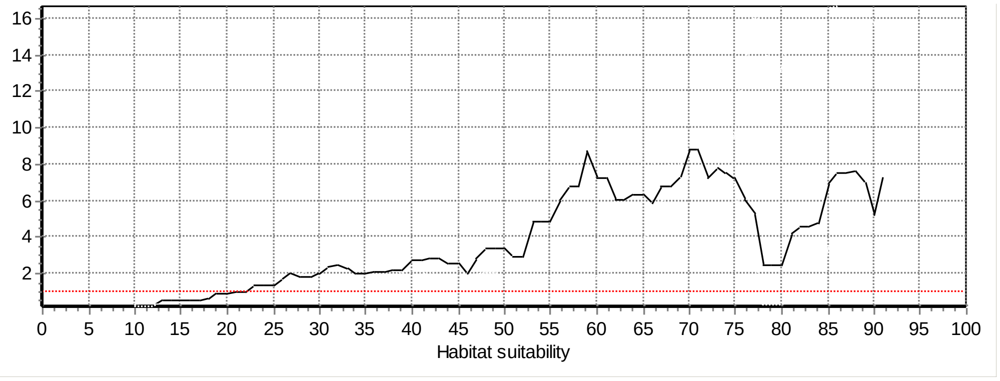

Figure 3.22 Baseline4 P/E ratio curve. Also shows a weak HS values between 40-90 show very erratic 95% confidence intervals (dashed lines), which indicates that this model is not very robust in predicting these HS classes, with the exception of HS classes around 67-70. Therefore, this model was also not selected.

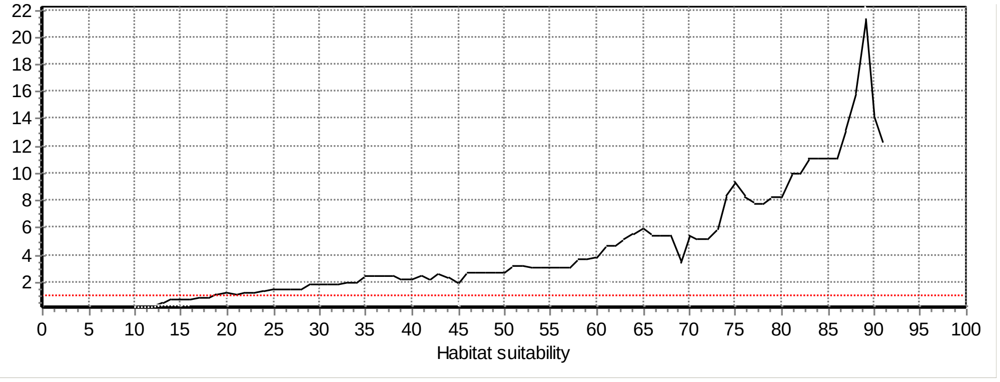

Figure 3.23 Baseline5 P/E ratio curve. Shows a relatively good model, however, one drawback is that the 'optimal' values between HS=70-95 shows rather erratic 95% confidence intervals (dashed lines), and so does the median line (solid) which indicates that this model is slightly less robust in predicting the higher/optimal HS classes.

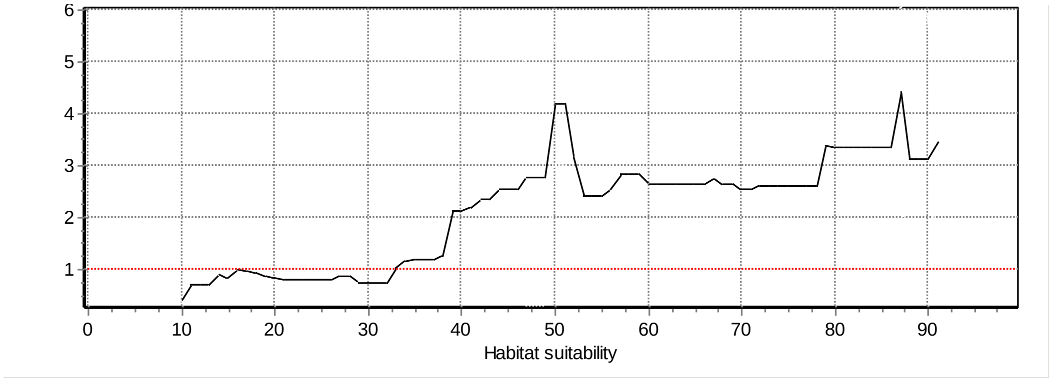

Figure 3.24 Baseline6 P/E ratio curve. This is an erratic curve - the 95% confidence interval shows huge variance between HS classes 40-55 and 78-90, indicating the model is not robust in predicting these HS classes. Also the slope of the curve is almost plateau-like between HS classes 60-78, rather than increases steadily as would be expected from a good model which modelled the higher optimal classes well. Therefore, this model is also not selected.

At the landscape level, the habitat suitability for *Tradescantia* (Figure 3.25) is based on both climate (MTminJ-A) and land cover (riparian classes and landscape-level indicators such as proximity to urban, proximity to roads, and proximity to streams). This map was then re-classified (as per the national level analysis), into Core, Marginal and Unsuitable Habitats as: (1) HS≥50 for Core areas; (2) 10≤ HS ≤ 50 for Marginal areas and (3) HS≤10 for Unsuitable areas. The result of this reclassification is shown in Figure 3.26. These variables produced a habitat suitability ranking as follows:

1) **Core Areas:** were situated in the lowland, coastal areas where all major urban settlements were concentrated (Orange); followed by semi-rural areas (white) and upland rural areas (white and yellow). The highest suitability classes were all primarily associated with the location of the main human-disturbance factors: higher urban concentrations, higher road network densities and streams in lowland, downstream areas.

2) **Marginal Areas:** these were typically in midland to upland rural areas outside the main urban centres and a large part of the urban coastal strip of Papamoa and inland from there.
3) **Unsuitable Areas:** were located primarily in the upland Kaimai Ranges and Matakana Island, but were also distributed in primarily rural areas which were over 10-15km from the nearest urban settlement (black).

The habitat suitability at the landscape level will be further discussed in Section 5.6.

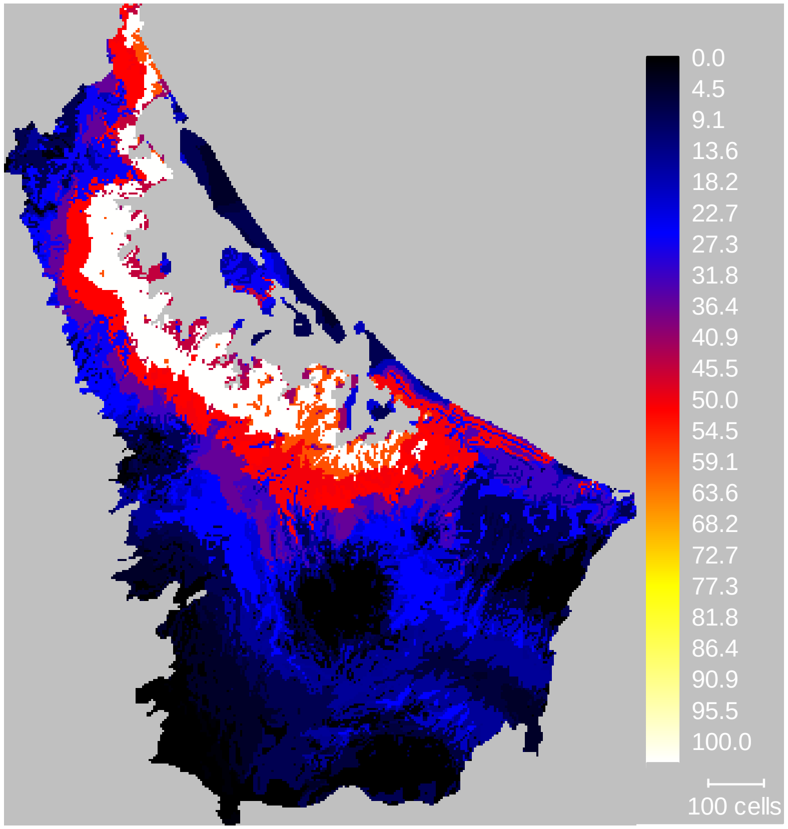

Figure 3.25 Habitat suitability for *Tradescantia* at the landscape level using ENFA. The values 1-100 are a measure of the Habitat Suitability, with 0 being unsuitable and 100 being optimally suitable for *Tradescantia*.

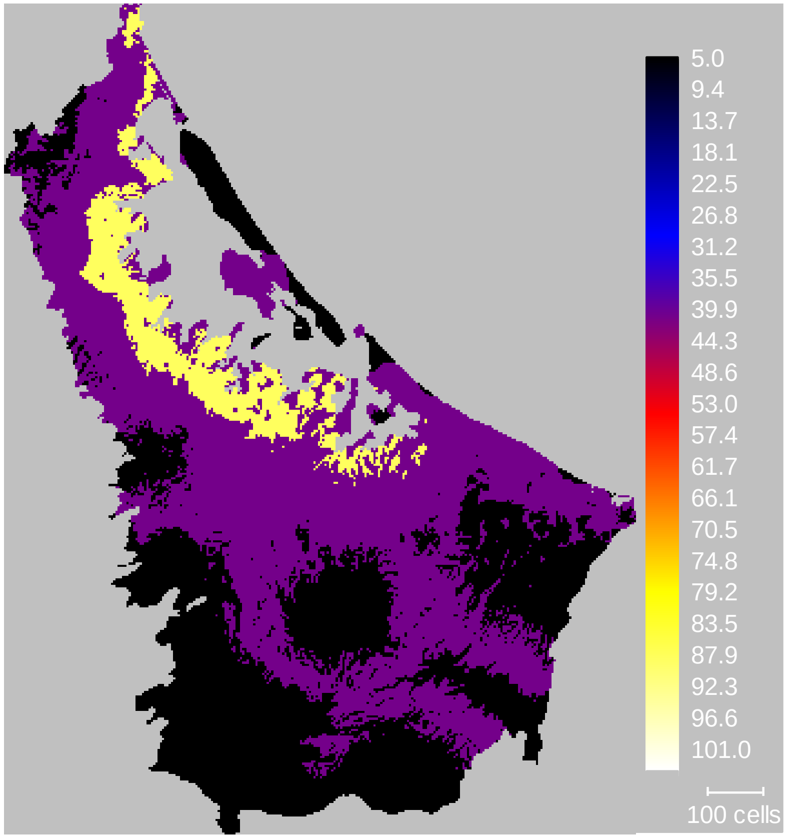

Figure 3.26 The core (yellow), marginal (purple) and unsuitable (black) areas for *Tradescantia*.

3.5.4.3 Validation of the ENFA-BioMapper model results

The validation statistics were provided earlier as a part of describing the various model qualities generated. The Predicted/Expected curve (P/E curve) is provided in Figure 3.27 below. This shows that Baseline2 is overall the best validated model, based on its P/E curve given its steady increase in P/E ratio with an increase in the HS classes, and a reasonable 95% confidence interval around the median line (solid), although it shows slightly more variance in the higher HS classes. This indicates that the model is quite robust in predicting the Habitat Suitability classes albeit slightly less confidence in the higher classes.

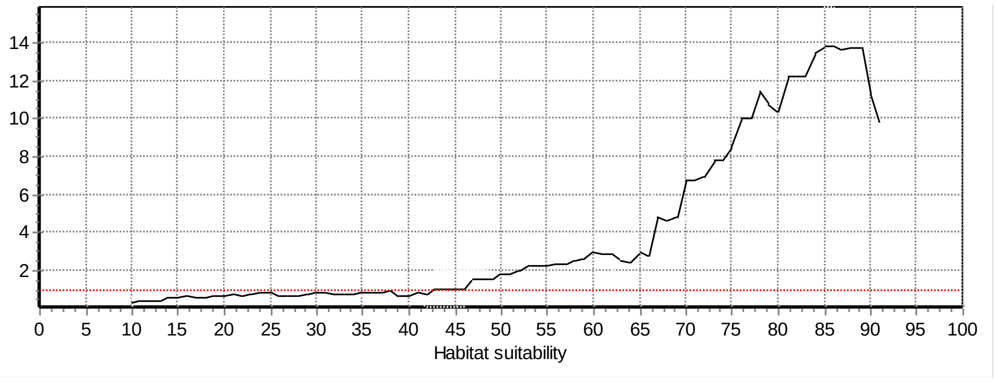

Figure 3.27 Baseline2 P/E ratio curve. This is a good model, in that the curve shape is also similar to the ideal graph shown in Figure 3.10 for the Continuous Boyce Index, and to Figure 3.20. Importantly, it shows a steadily increasing P/E curve for HS classes >60, which indicates that it predicts the optimal classes well (also shows a 95% confidence interval which is quite steady around the solid median line). However, between HS= 89-90, the P/E curve decreases sharply.

Model Baseline2 was used in the extrapolation exercise at the landscape level in Chapter 6, because it performed well in the baseline modelling and also because used EGVs at a spatial resolution of 50m x 50m, this scale was appropriate for the extrapolations.

3.6 Discussion of the spatial distribution of Tradescantia

The spatial distribution of *Tradescantia* was modelled based on the selected climatic land use and landscape-level factors and their associations derived in Chapter 2 at two scales: (1) national and (2) landscape. The main ecological concepts that influenced the species distribution modelling and its outputs in this context were: direct versus indirect predictors, the ecological niche (further classified as fundamental versus realised niches), and equilibrium versus non-equilibrium. These concepts will be discussed in this Chapter, with further discussions in Chapter 7 following the integration of climate and land use change scenarios in Chapter 6.

Two GIS-based, presence-only modelling methods were selected and implemented: BIOCLIM and Ecological Niche Factor Analysis (ENFA). The outputs were spatially-explicit habitat suitability maps, equivalent to the species realised distribution, representing the realised ecological niche for *Tradescantia*. The modelled habitat suitability at the national level was solely based on climatic variables (MTminJ-A and AWD). These two variables represent climatic extremes, one of winter minimum temperatures and the other of water stress in the driest months (average of November, December, January and February deficits).

The outputs of both models showed broad agreement in delineating similar areas to the highest suitability classes and to the unsuitable class. To interpret the habitat suitability outputs further, the Land Environments of New Zealand classification (Leathwick et al., 2003) will be used descriptively as it provides all dominant vegetation and land form characterisation needed to explain the dominant patterns observed in *Tradescantia*'s national distribution.

The dominant pattern to emerge is that *Tradescantia*'s most suitable habitats are located within lowland environments which contain almost 70% of the urban areas in New Zealand, including greater Auckland, and 39% of horticultural land. Both urban and horticultural land cover classes were shown to be associated with *Tradescantia* species distribution in Chapter 2, as these are the two classes in which human propagation of *Tradescantia* is most prevalent (in gardens, in orchard hedgerows, and in understorey groundcover in kiwifruit and other orchards). Most of the landscapes in these areas are highly modified and converted to pasture for dairy, cattle and sheep farming and so indigenous vegetation is reduced to small remnants which are often degraded by multiple weed problems and nutrient disturbances.

Other areas were unsuitable for a variety of reasons. The top of the North Island was unsuitable because of sand dunes and climate creating high AWD and wetlands, and low human settlement. The Central Volcanic Plateau is largely inhospitable for frost-sensitive plants like *Tradescantia* because of extreme cold winter minimum temperatures. The adjoining mountain ranges including Mount Tarawera, Uruwera Ranges, Kaimanawa Ranges are primarily uninvaded by *Tradescantia* because the vegetation is largely intact with little permanent human presence. Parts of Hawkes Bay and Wairarapa have higher rainfall deficit and vapour pressure deficit and low fertility soils, coupled with high native vegetation clearance which has formed vast agricultural plains with few safe sites for *Tradescantia*.

The landscape-level ENFA analysis showed a different suitability ranking to the national-level one for the case study region. The national-level ENFA analysis showed that climatically (based on the MTminJ-A and AWD combination), there were no unsuitable areas; instead the entire case study area fell within the highest suitability classes. However, when riparian habitat variables and landscape-level proximity variables were introduced into ENFA, the habitat suitability was recalculated, and as a result, areas delineated at the national level as climatically suitable were reclassified as unsuitable at the landscape level.

Since the outputs from the BIOCLIM and ENFA modelling were based solely on the observed presences of *Tradescantia* in a novel environment (New Zealand), they represent the ‘realised’ niche or distribution of *Tradescantia* in New Zealand, and not the ‘fundamental’ niche of this species. The fundamental niche (described in Section 3.2.3), by comparison, is based on physiologically-derived thresholds, e.g. a temperature threshold of -4^{o}C. Habitat suitability based on the fundamental niche would be distinctly different to both the BIOCLIM and ENFA outputs at the national scale, for example, in the South Island climatic suitability would extend inland by sharply into upland areas from the coast in some places. This mismatch is due to the fact that no *Tradescantia* observations are available at these inland locations, either because no data records are available or because *Tradescantia* is much less prevalent or absent from these areas. The latter reason is more likely because the West Coast has high-gradient mountains in close proximity to the coast, mostly in protected national parks, which would mean that human settlement is low to absent.

In Chapter 4, the development of land use change scenarios will be described, along with how this relates to various biodiversity indicators at the case study landscape-level within the integrated assessment methodology. This will provide the context for interpreting the species distribution model results at the landscape level, both under baseline and future scenarios of land use change.

3.7 Summary

- Two presence-only GIS modelling methods, BIOCLIM and ENFA, were chosen and implemented to produce the baseline spatial distribution of *Tradescantia fluminensis* at the national (New Zealand) and landscape level (Western Bay of Plenty-Tauranga).
- There was broad agreement between both methods for the habitat suitability of *Tradescantia* at the national scale, based on MTminJ-A and AWD as the primary delimiting variables (indicators of minimum temperature stress and frost, and water or drought stress respectively).
- At the landscape level, ENFA produced a new habitat suitability ranking map, based on climatic (MTminJ-A) + land cover (riparian) + landscape (proximity to urban, roads and streams) variables, which modified the suitability ranking (compared to the national-level ranking based solely on climatic variables) for the case study landscape. This refined habitat suitability map provides adequate representation of human-induced invasibility at the landscape level, which has a dominant influence on propagule pressure, establishment and spread of *Tradescantia* at the regional landscape level.

4 Chapter 4: Land-use change scenarios at the landscape level

4.1 Introduction

This chapter develops land-use change (LUC) scenarios for the integrated assessment, at the landscape-level, for the Western Bay of Plenty and Tauranga. Land-use change affects the extent and spatial distribution of *suitable habitats*, *disturbance sources* and *dispersal mechanisms* linked to the invasion and distribution of *Tradescantia fluminensis*. Hence, land use change as it relates to landscape-level invasion for *Tradescantia* is reviewed in Section 4.2, approaches for developing future land use scenarios (applicable to *Tradescantia*'s broad invasion strategy at the landscape-level) are reviewed in Section 4.3, and an appropriate approach selected to test the sensitivity of landscape invasibility to land-use change in Section 4.3. A description of the case study subregion is given in Sections 4.3-4.4, highlighting the spatial and policy-level context of land use changes projected to a time horizon of 2050 given constraints for allocation of urban growth based on: ecological constraints, highly versatile land, and rural land allocation for production. In Section 4.4, land use change scenarios at the landscape-level are derived that incorporate 'Storylines' which describe alternative scenarios of changes to: (1) suitable habitats, (2) disturbance, and (3) dispersal of propagules of *Tradescantia*. The resulting landscape-level LUC scenarios are assessed in Section 4.5 and conclusions are drawn in Section 4.6.

The four scenarios of land use changes derived to test the landscape sensitivity for this study are: (1) the baseline land use scenario; (2) the 'SmartGrowth' scenario; and (3) the 'Build-out' scenario.

4.2 Land-use change (LUC) at the landscape-level

The main interlinkages of land use change to invasion at the landscape-level were reviewed in Chapter 1, Section 1.1.2.2. In Chapter 2, Section 2.5, the case study landscape was described in landscape terms with respect to its association with the species distribution of *Tradescantia*. Here, the link to land use change is addressed. To link land use, land cover and *landscape-level change* to an invasive species like *Tradescantia* and changes to invasibility at the landscape-level, the work of With (2002) provides a very useful conceptual schematic. With (2002) links the typical stages of an invasion process, with associated landscape-level effects, which are directly related to land use and land cover (and therefore, land-use and land-cover change), showing that land-use change can increase invasibility and the spatial distribution of an invasive species by some of the following means:

1) increasing the frequency of introduction of the species (or multiple species) through land use (e.g. garden planting);
2) altering the potential number of sites available for colonization by a species either due to direct disturbance that may newly create a suitable colonizing substrate, or alter the availability of a resource needed for growth (e.g. light or nutrients), and by re-colonization of sites where the species has experienced local extinctions;
3) altering the spatial configuration of suitable habitats that promote the survival and persistence of the invasive species, for example increase in edge habitats that are disturbed and provide microclimatic gradients of light and nutrients that promote invasive species growth;
4) altering the spatial configuration of dispersal conduits such a streams and rivers, roads and track and proximity to areas of human settlement where invasive plant propagules can be dumped into adjacent and suitable habitat for establishment and persistence across the landscape; and
5) altering the distribution of populations which are able to provide propagule sources for new populations to establish in proximity (short to medium distances) or by long-distance dispersal (for instance downstream dispersal over kilometres, via streams and rivers) which will over time continue to expand and intensify the landscape-level prevalence of the invasive species and its spatial distribution, also leading to persistence of the species in the landscape.

Figure 4.1 shows the conceptual schematic by With (2002).

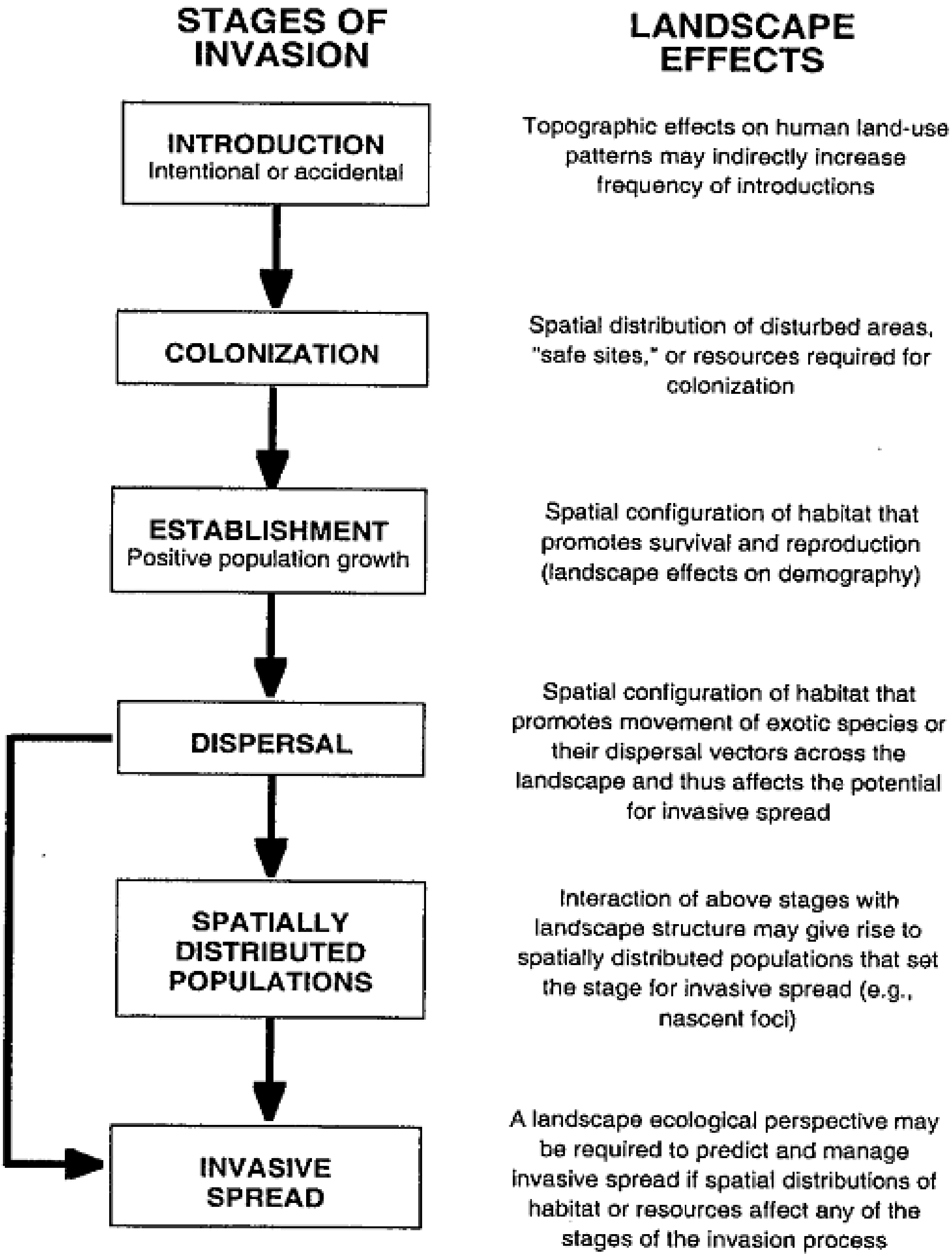

Figure 4.1 Linking land use and landscape effects on invasive species spread and distribution. The development and multiplication of self-sustaining source populations across the landscape and the spatial pattern and configuration of these population and suitable habitats, dispersal conduits and sources of disturbance or resources all combine to influence the spread and distribution of the invasive species over time at the landscape-level (Source: With, 2002, pg. 1193, used with permission).

Land-use changes, leading to fragmentation and isolation of patches in the landscape (through vegetation clearance for example) and the spatial distribution of an invasive species can be better understood by considering localised populations of the species as ‘metapopulations’, i.e. disjunct/geographically separated populations of a single species or group of species, that form in response to fragmented landscapes (Hanski, 1991). Land use-related landscape changes influence the metapopulation structure and persistence of a species in a landscape and hence the spatial distribution of a species or group of species at this scale, by changing the occurrence of colonization and extinction events of a species at suitable habitat sites. Some of the disjunct populations of the focal species (such as *Tradescantia*) will be ‘source’ populations (where net emigration of viable propagules occurs which start new satellite populations in the landscape). Other populations act as ‘sink’ populations (where net immigration of viable propagules occurs from other source populations). A study by Opdam and Wascher (2004) explains that landscape-level land-use changes (such as habitat fragmentation) and climate change have potential synergistic effects on species distribution such that two levels of spatial scale interact: the metapopulation level (landscape) and the larger scale species geographic range. In landscapes where the degree of habitat fragmentation or loss still allows for species metapopulation persistence over time, the overall species range/distribution, though restricted, will continue to expand. However, in landscapes where the level of habitat fragmentation or loss is high, species metapopulation persistence may be hindered or blocked altogether hence reducing the species range/distribution (Opdam and Wascher, 2004)[32].

Changes to the level of fragmentation of suitable habitats, the spatial extent and the connectivity, take place through land-use changes which result in either: 1)

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[32] However, the effects on metapopulation dynamics for an invasive species versus a native plant species may be quite different, and more research attention is needed in this area to make comparisons, given that increasing fragmentation and creation of edge dominated habitat may increase the invasibility of the landscape, and the metapopulation persistence of an invasive species, while conversely reducing the metapopulation persistence for a native species.

vegetation clearance (loss) or 2) re-vegetation and habitat restoration (gain) at the landscape level (especially for indigenous vegetation). For instance, by developing connectivity zones such as extensively restored riparian networks, a landscape with a higher density of small semi-natural landscape elements eventuates. This increases the 'permeability' or potential for movement, across the landscape (Opdam and Wascher, 2004), for a focal species that uses these as corridors both for dispersal and for new source/sink populations in suitable habitats. This dispersal-enhancing effect of riparian areas is particularly true for ruderal or early colonizing species which respond positively to disturbance at the landscape-level (Tabacchi et al., 1996). Once established as a colonizing species, species such as *Tradescantia*, for example, are known to persist indefinitely, or until a local disturbance such as a flood event destroys the population, causing local extinction of that population and which may in time also be the site for re-colonization. In the case of *Tradescantia,* field workers from the Wellington Regional Council and the Environment Bay of Plenty Regional Council have reported that after a local extinction event, *Tradescantia* is known to re-colonize sites effectively in a short time.

As described in Chapter 1 and 2, of invasive species generally, as suitable habitats become more fragmented this increases the invasibility. However, fragmentation and habitat loss also decreases the connectivity of suitable habitats, increasing inter-patch distances. Ruckelshaus et al. (1997) found that dispersal success between patches increased as suitable habitat increased and decreased as fragmentation increased though both effects were weak. However, propagule pressure or the rate at which viable propagules (such as seeds, or vegetative fragments for instance) are released from a source population into a new site(s) is a dominant factor in determining the successful establishment, spread and distribution of an invasive species at a site-specific level, as shown by various studies (Von Holle and Simberloff, 2005; Colautti et al., 2006). Increased propagule pressure may play a significant role (along with aided dispersal by water, humans, and stock, for example) in overcoming the reduced connectivity due to fragmentation.

In the following section, various approaches to developing land-use change scenarios which can address these questions are reviewed. The most appropriate approach for developing the land-use change scenarios to assess broad *changes to invasibility*, at the landscape-level is selected. This builds on the landscape-level indicators/variables described and used in Chapters 2 and 3 respectively and therefore is designed to build on the analysis of the baseline/current distribution of *Tradescantia*.

4.3 Methods for developing LUC scenarios

Land-use change (LUC) scenarios are important tools for integrated assessment of species distribution changes. Direct links exist between human-induced modification of land uses and subsequent spatial and temporal changes in ecological systems at the landscape-level (for instance through fragmentation of native vegetation, and alteration of nutrient dynamics). Scenarios are generated at multiple scales from global to landscape-levels. According to Veldkam and Lambin, (2001) the common elements of all forms of land-use change are: that underlying drivers affect spatial and temporal changes; that drivers are scale dependent; and that land-use change can be assessed both in terms of its location and its quantity. They offer the possibility to test the sensitivity of land use patterns to changes in selected variables. They also allow testing of the stability of linked social and ecological systems, through scenario building.

Scenarios provide a future spatial snapshot that is not necessarily constrained by current conditions. In landscape-level assessment, scenarios are useful in linking goals and assumptions of land use with alternative potential future spatial changes in land use. A complete scenario needs to include the current situation, a future state, and a means of implementation. Without all three of these elements, scenarios face the risk of being critiqued as ‘utopian’ and disconnected with the landscape context being assessed. Scenarios are different from forecasts, in that they do not attempt to predict the outcome of land-use change. Instead scenarios pose and answer a series or ‘what if’ questions. Scenarios can be based on mathematical models, however, this is not a rule. Scenarios can also be developed that are more normative. Scenarios are particularly useful in integrated assessment for species distribution changes. Luoto et al. (2007) found that at finer resolutions of environmental data (typically used in regional and landscape-level analyses), land cover/land use improves the performance of species distribution models. Their results suggested that climate variables were large-scale determinants, followed by land cover/ land use related variables at finer resolutions. Hence climate change scenarios need to be combined with land-use change scenarios in assessing vulnerability and sensitivity at landscape-level integrated assessment which utilises finer resolution datasets for spatial analyses.

Two fundamental types of scenarios can be defined: state and process. A ‘state’ scenario describes a future situation without articulating the steps or events needed to get there. A ‘process’ scenario provides a ‘roadmap’ of assumptions, events and steps needed to get there (Hirschorn, 1980). Process scenarios are the most appropriate at the landscape-level. Two possible scenarios types are identified. Firstly, ‘forecasted’ or ‘beginning state driven’ scenario projects current trends and control practices to produce a trajectory on which a possible future may be conceived. A common forecasted scenario in landscape planning is the ‘build-out’ in which current land use controls are used to determine a theoretical or maximum level of built development. Build-outs do not represent predictions, but establish a theoretical maximum level of development as a baseline for comparison with other development alternatives. In contrast, a ‘backcasted’ or ‘end state driven’ scenario, is based on an idealised concept, or vision, of what the future could be. Backcasted scenarios are often designed to articulate and visualise the spatial consequences of planning goals or assumptions and the steps necessary to accomplish them (Schoonenboom, 1995). In many cases, alternate scenarios are developed with the explicit purpose of demonstrating a range of alternatives.

In addition to the above-mentioned normative methods for developing scenarios, numerous model-based scenario generators have been developed to represent land-use changes spatially, from different disciplinary backgrounds (Verburg et al., 2004), including socio-economic, agro-ecological or urban growth models through to biodiversity, forestry and conservation-orientated land-use change models.

Global-scale LUC models often generate scenarios using narrative 'storylines' of possible futures which associate various qualitative combinations of factors such as demographic, technological, and policy-related changes (Arnell et al., 2004; Veldkamp and Lambin, 2001). In several cases these narrative storylines are in fact aligned with the IPCC Special Report on Emissions Scenarios (SRES) scenarios for alternative socio-economic pathways at the global scale and can also be applied at smaller scales (e.g. national and regional) (Audsley et al., 2006; Abiltrup et al., 2006; Rounsevell et al., 2004, 2005 and 2006). Audsley et al., (2006) and Rounsevell et al., (2005) in particular, use the SRES scenarios to develop explicit spatial allocation rules for land use change with respect to agricultural land use change, at the European continental scale. At the more localised scale, landscape change models generate scenarios where changes to spatial structure and configuration of key processes or habitats, for instance, are measured using spatially-explicit indicator variables and assessed for change given various endogeneous and exogeneous land-use change drivers and constraints. At the landscape-level, variables of location, extent, configuration and connectivity of suitable habitats, disturbances, resources, source and sink populations of a species, can be integrated with the socio-economic, policy-related and other drivers that effect change to these spatial variables/indicators within a Geographic Information System (GIS), to assess land-use change in terms of changes to patches, corridors and the surrounding matrix.

Landscape patterns can be quantified using spatial landscape indices or metrics to characterize and quantify landscape composition and configuration for scenario development. These metrics may include the number of patches, area, patch shape, total edge of patches, nearest neighbour distance, landscape diversity, interspersion and contagion metrics to represent landscape patterns. Recent studies have applied landscape metrics to quantify landscape patterns (Cushman and Wallin, 2000; Weinstoerffer and Girardin, 2000; Lin et al. 2002; Remmel and Csillag, 2003; Fortin et al., 2003; Berling-Wolff and Wu, 2004; Li and Wu, 2004; Kearns et al., 2005).

Landscape-level scenarios are particularly useful, in integrated assessment for species distribution changes. Luoto et al. (2007) found that at finer resolutions of environmental data (typically used in regional and landscape-level analyses), land cover/land use improves the performance of species distribution models. Their results suggested that climate variables were large-scale determinants, followed by land cover / land use related variables at finer resolutions. Hence, climate change scenarios need to be combined with land-use change scenarios in assessing vulnerability and sensitivity at landscape-level integrated assessment which utilises finer resolution datasets for spatial analyses.

Table 4.1 provides a comparison of a few of the studies which do incorporate process-based and model-based simulations of land use change scenarios for use in integrated assessments. Where these assessments have been integrated with climate change, this is also indicated. For this study, elements of the process-based scenario development approaches will be used to produce ‘static’ alternative scenarios of future land use change at the landscape-level for the Western Bay of Plenty-Tauranga. Narrative storylines of the combination of changes relating to urban development and road networks (disturbance) and biodiversity restoration (suitable habitats) and dispersal pathways will be integrated in each of the scenarios produced. The process-based forecast scenarios are chosen over the model-based approaches, because these land use change scenarios are meant to test the sensitivity of specific ‘future states’ of urban development (i.e. ‘SmartGrowth’ and ‘Buildout states’) and specific spatial biodiversity restoration targets (for proposed new vegetation planting and Environmental Enhancement mainly in riparian networks) for the case study landscape. In other words, this study is not looking to build scenarios that test multiple dynamic trend-based predictions of land use change based on modelled system components, for which model-based methods are more appropriate.

LUC scenario	**Major Focus of LUC scenarios**	**Information sources**	**CC scenarios (Y/N)**	**Time horizon**	**Reference Examples**
Process	Habitat change for multiple species of alpine plants. Testing a scenario of ‘Land abandonment’ from pasture and climate change.	Spatial and cadastral information on land parcels	Y	2050	Dirnboeck et al., 2003
Process	Changes to future threats to biodiversity from LUC +CC Red List Species of *Proteaceae* in South Africa, threat status change with LUC+CC	Information on untransformed protected areas, and forecasts (%Δ) for urban and cultivated areas	Y	2020	Bomhard et al., 2005
Process-forecasted	Impacts of land development on biodiversity at the landscape level. Four alternative LUC scenarios such as: ‘present’, ‘plan-trend’, ‘buildout’, ‘spine’, ‘southern’ and park’ each representing a distinct development pathway.	Habitat maps, species data.	N		White et al., 1997; Syphard et al., 2005.
Model-based	Protected area buffer zone management with future land use change in Nepal.	Demographic, livestock, land use and milk production data	N	2025	Hjortsø et al., 2006.
Model-based	Integrated LUC scenarios for Europe incorporating: (1) ‘qualitative’ descriptors of major LUC drivers using SRES scenarios storyines (2) ‘quantitative assessments’ of the total area requirements for each land use type and (3) spatial allocation rules (specific to each scenario) to locate the specific land use quantities available for Europe.	Reviews of literature, expert judgement and modelling techniques.	N	2020, 2050, and 2080.	Rounsevell et al., 2004, 2005 and 2006; Audsley et al., 2006.

Table 4.1 Comparing LUC modelling methods in particular process-based and model-based scenario simulations.

4.4 Description of the case study area

4.4.1 Overview

A description of the case study area for which the scenarios were developed, provides further context for the development of the land use change scenarios, given the land use change classes, the land use constraints (based on land capabilities and ecological constraints) particularly on urban development. Many of the ecological constraints were developed as apart of the SmartGrowth 50-year long term growth planning initiative undertaken by the Western Bay of Plenty District and Tauranga City Councils.

The Western Bay of Plenty District and Tauranga City are located adjacently as a subregion, within the Bay of Plenty region on the eastern coast of the North Island of New Zealand (see Figure 4.2). The subregion is one of the fastest growing in the country: extending from Ohinemuri to the Whakatane District Boundary and is bounded by the Kaimai range to the west and the Pacific Ocean to the east. The subregion has been an area of rapid population growth since 1950. The population in 2001 was 130,000 – a 14.5% increase from the previous census in 1996. It is recognised as ‘sunbelt’ destination, with 80% of growth resulting from migration.

The landform is rolling to steep with extensive coastal plains. The total area of the sub-region is 2289 km^2. Tauranga Harbour is a significant natural feature and it is also an area of recreational value and commercial port use (Port of Tauranga). Tauranga is the main urban area (70% of the sub-region’s population, with smaller settlements of Te Puke, Katikati, Waihi Beach, Omokoroa, and Maketu. The Western Bay of Plenty consists of broken contour, with areas of flat land on the coast, rising inland to over 600 meters in the Kaimai ranges. Large areas of flat land are scattered in small pockets amongst the broken contour. Numerous streams and rivers drain the eastern slopes of the Kaimai Ranges and have carved deep gorges in the land surface. In the coastal lowlands, the streams are less deeply incised and open out into swampy estuaries and mudflats around the Tauranga Harbour. Extensive coastal swamps are found in the eastern reaches. Running inland, south of Tauranga City and the township of Te Puke, are several plateaus containing hundreds of hectares of flat land lying between deep gorges. To the east of Te Puke, in the Paengaroa, Pongakawa, and Pukehina areas there are large flats as well as coastal swamps (Wakeford, 1981). See Figure 4.3 for an aerial view of the case study area showing the features described.

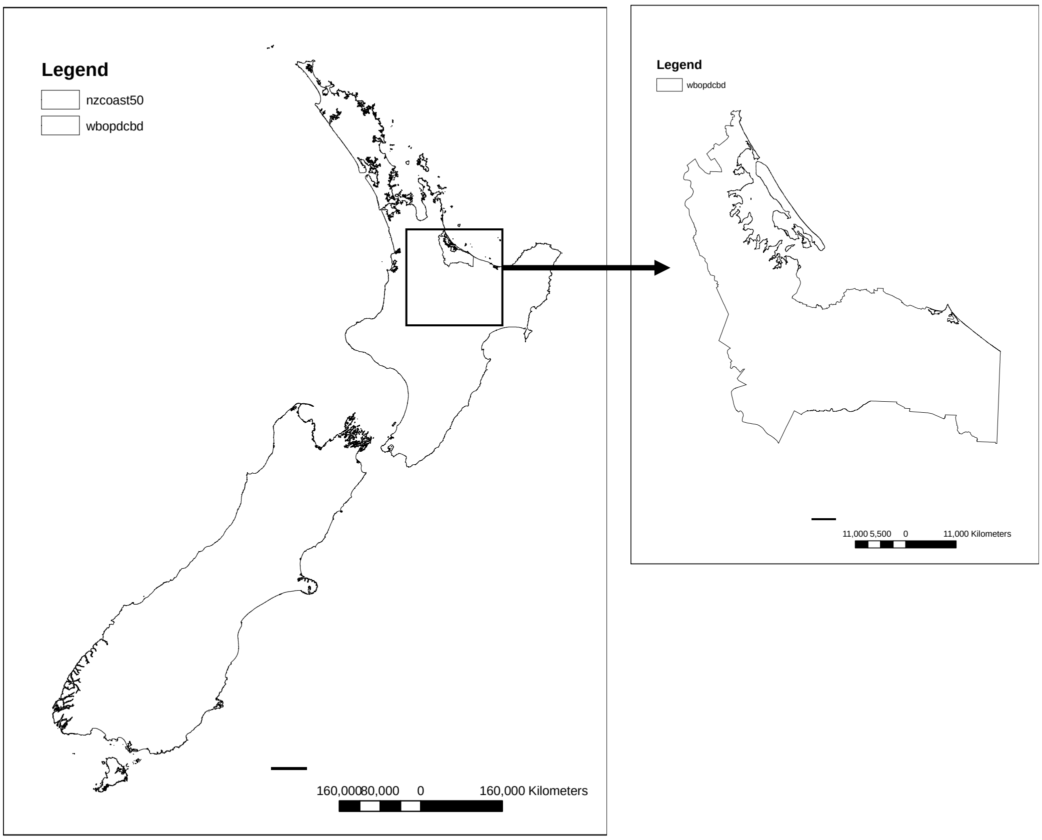

Figure 4.2 Case Study Area, showing New Zealand (left) and Western Bay of Plenty District (right insert).

The subregion has undergone vast changes to its pre-human land cover. Extensive swamps were located to the east of the District, while around Tauranga Harbour there were extensive freshwater and saline wetlands. Many more species of birds, animals and fish were present, including some species now extinct such as the huia. In the course of several centuries of Maori occupation, much of the original forest cover was cleared by fire and replaced by manuka and fern (Wakeford, 1981).

Figure 4.3 Colour Aerial View of the Case Study area, showing the extensive intact indigenous forest of the Kaimai Ranges (upper to mid-left); dendritic gully and riparian vegetation (lower left); and fragmented lowland mixed use landscape (Data produced and supplied by Global Aerial Surveys Ltd, Kaimai 2 Coast).

Ecological issues facing the subregion include (SmartGrowth, 2007):

1. The ***Tauranga Ecological District*** includes coastal and semi-coastal bioclimatic zones. Freshwater wetlands and terrestrial ecosystems have been severely reduced in size and modified. Relatively little indigenous vegetation remains except around the margins of the Tauranga Harbour. Most indigenous remnants are degraded by weed invasion but are still of significance. Only 0.6% of land in the coastal zone and 1.2% in the semi-coastal zone is protected.
2. The ***Otanewainuku Ecological District*** includes coastal, semi-coastal lowland, with a strip of montane bioclimatic zones. About two-thirds of the district is in the sub-region. The main characteristics of this district are its plateaus and gorges. Overall 23.4% of it is protected, although the semi-coastal zone is under-represented in the reserve system with only 8.9% protected.
3. The ***Te Aroha Ecological District*** is mostly semi-coastal and lowland, with a strip of montane forest on the crest of the Kaimai Range. Over a third of the district is in the sub-region. Most vegetation types in the semi-coastal zone are present as minor remnants and some are not represented in protected areas. Only 15% of the lowland zone and 30% of the montane zone are protected.
4. The ***Waihi Ecological District*** extends south from Whangamata to Waihi Beach. Only a very small portion of the district is included in the sub-region as coastal and semi-coastal zones. Small remnants of the original forest remain and very little of it is protected.
5. Areas of high ecological significance are those with remaining indigenous vegetation and habitats (including harbours, wetlands, freshwater streams and rivers, remaining areas of indigenous vegetation and protected areas).
6. Areas of moderate significance are degraded natural areas with restoration potential, vegetation comprised of a mixture of indigenous and exotic species, and degraded drainage systems. Intensive development adjacent to natural areas will need to address threat-related issues noted above. This may impose some limitations on the types of activities allowed or encouraged.

4.4.2 Climate

The climate throughout the region is mild with above average (for New Zealand) annual sunshine hours (2200 hours). The sub-region has a warm sunny climate (an average of 1,900-2,300 hours per year) with moderate rainfall (1,200-2,400mm per year), making it one of New Zealand's most productive horticultural areas (in particular for kiwifruit and avocados), particularly around the towns of Te Puke and Katikati. Temperatures vary from a mean daily maximum in January of 25°C to a mean daily maximum in July of 14°C. Droughts are not uncommon in the coastal areas in the warm summer months of January and February. Wind velocities are moderate but shelter is necessary for protection against winds prevailing from the south-west. Coastal areas can also be exposed to strong winds from the north and east. Changes to extreme events are projected to happen for the subregion, as projected by the National Institute for Water and Atmospheric Research (NIWA) (MfE, 2005) such that a 1-in-20 year event is projected to happen between once every 2.5years and once every 5years in the 2080s, under a medium-high climate change scenario. Figure 4.4 shows the spatial pattern for mean annual temperature in the Bay of Plenty region, with highest temperatures distributed in coastal edges and lowland areas of the Western Bay of Plenty and Tauranga.

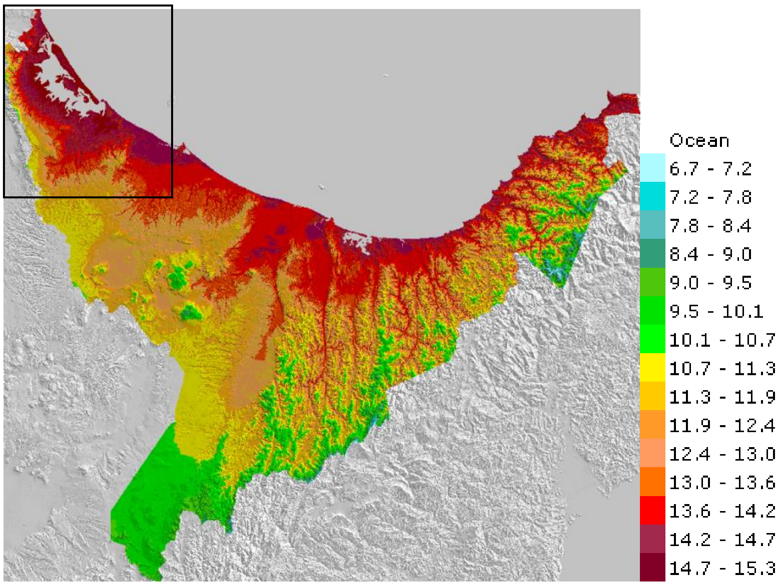

Figure 4.4 Mean Annual Temperature for the Bay of Plenty region with the insert box indicating the case study sub-region of Western Bay of Plenty-Tauranga. Darlam GCM scenario, mid climate sensitivity (CLIMPACTS).

4.4.3 Land Use

Dairying is the main farming enterprise on the coastal plains. Further inland sheep and beef farming are predominant in areas not undergoing horticultural development. A recent innovation in land use has been the introduction of deer farming. Native bush, unimproved scrub, and exotic forests cover large areas of the Bay of Plenty. Approximately 30 per cent of the area of Tauranga-Western Bay of Plenty subregion is inhabited hill country. The major areas being in the Kaimai Ranges, the upland areas west of Te Puke, and the Kaharoa plateau. In response to overseas and internal market demands, there has been a rapid development towards horticulture. The Bay of Plenty region is now an important source of citrus, subtropical fruits and vegetables for local and overseas markets. The main fruit growing areas are situated on the plateaus and pockets of flat land scattered throughout the western and eastern Bay of Plenty. Land sloping to the north and north-east is preferred for horticultural development. These areas offer protection from the cold and strong winds which come from the south and west. The flat coastal and inland areas around Te Puke and Whakatane districts are more susceptible to frosts and cold winds. Horticultural development is taking place in these areas but many are not yet fully proven, e.g. The Maketu district, east of Te Puke (Wakeford, 1981).

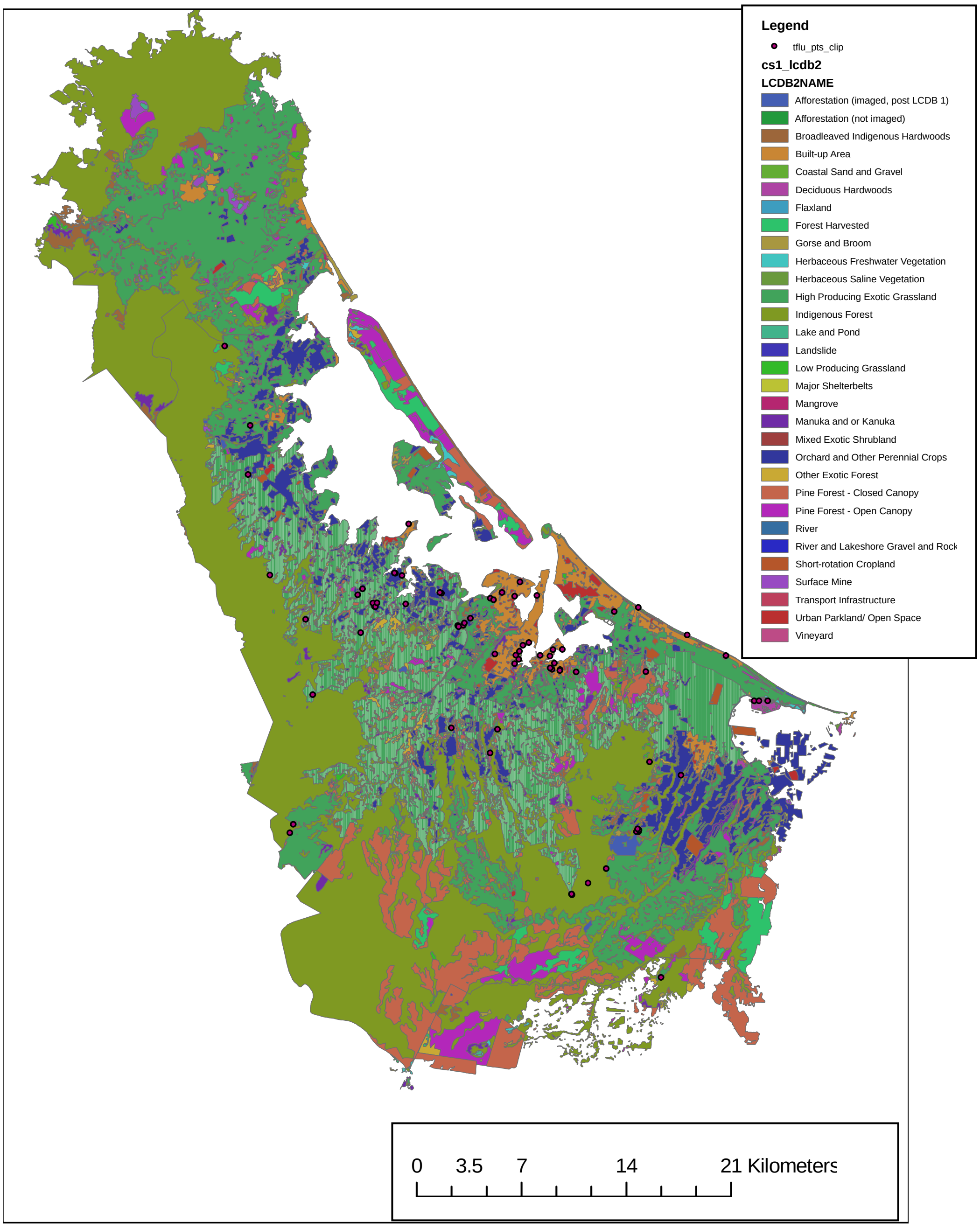

Figure 4.5 Land use classes from the Land Cover Database, LCDBII. Table 4.2 provides a further breakdown of the area (ha) and percentage of the case study area covered by each LCDBII class.

The dominant land use classes are indigenous forests and high producing exotic grassland together accounting for over 73% on the land area, followed by a further 10% in pine forestry and 7% in orchards (horticultural) and other perennial crops. Urban areas though they cover a small area of about 2.8%, exert a dominant effect on regional growth and development along with the dairy and horticulture sectors.

Land Cover/Land use Class	Area (ha), rounded to nearest whole no.	% of the Study Area
Indigenous Forest	8330	39
High Producing Exotic Grassland	7231	34
Pine Forest - Closed Canopy	1571	7
Orchard and Other Perennial Crops	1409	7
Pine Forest - Open Canopy	608	3
Built-up Area	593	3
Forest Harvested	402	2
Broadleaved Indigenous Hardwoods	283	1
Manuka and or Kanuka	212	1
Other Exotic Forest	143	1
Urban Parkland/ Open Space	114	1
Gorse and Broom	96	<1
Short-rotation Cropland	88	<1
Afforestation (imaged, post LCDB 1)	74	<1
Low Producing Grassland	70	<1
Surface Mine	54	<1
Herbaceous Saline Vegetation	47	<1
Deciduous Hardwoods	41	<1
Herbaceous Freshwater Vegetation	38	<1
Major Shelterbelts	31	<1
River	22	<1
Lake and Pond	19	<1
Coastal Sand and Gravel	15	<1
Transport Infrastructure	11	<1
Mixed Exotic Shrubland	7	<1
Afforestation (not imaged)	6	<1
Mangrove	5	<1
Vineyard	2	<1
Landslide	0	<1
River and Lakeshore Gravel and Rock	0	<1
Flaxland	0	<1

Table 4.2 LCDB2 Area per class and percent of case study in each class. Over a third coverage by indigenous forest and high producing exotic grassland.

In Section 4.5, which follows, the spatial context for developing the land use change scenarios for this study is provided.

4.5 Case study context of land use change to 2050

For the purpose of developing alternative land use change scenarios it is essential to understand the spatial and policy-level context for projected land use change to 2050 for the case study area. The subregion has taken a long term strategic planning perspective with a horizon of 2050 for regional land use planning, termed SmartGrowth, with its associated SmartGrowth Regional Settlement Strategy[33]. The purpose of SmartGrowth is: "To develop and implement a strategy for the sustainable development of the Western Bay of Plenty sub-region for the period 2000-2050" (Tremain 2001). Identifying ecological constraints was part of Phase 2 of the project, which includes the compilation of an implementation framework by December 2003. The Western Bay of Plenty is undergoing rapid population growth and could possibly reach 290,000 people by 2050 (Tremain 2001). This strategy aims to deal with the intense competition for prime land through strategic spatial development and environmental planning.

There are two main types of land preservation associated with SmartGrowth: (1) the preservation of land for parks, recreation, and greenways within built-up urban and suburban areas, and (2) the preservation of rural land for the production of food and fiber to maintain valuable natural areas—such as wildlife habitats and water supply sources—and to channel built development to more appropriate locations. Land versatility for food and fibre production, soil constraints on urban growth and ecological constraints are all integrated to identify the most suitable

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[33] The SmartGrowth Regional Settlement Strategy, is a joint project between Environment Bay of Plenty, Tauranga District Council (TDC), Western Bay of Plenty District Council, and local Maori (Tangata Whenua) (Tremain 2001). The study area extends from Waihi Beach in the north and to Otamarakau in the east, and inland to include most of the seaward-flowing catchments. It includes all of the Tauranga Ecological District, a large section of the Otanewainuku Ecological District, a significant area of the Te Aroha Ecological District, and a small part of the Waihi Ecological District.

areas to allocate projected population growth over a 50-year time horizon to the year 2050 further described in Sections 4.5.1-4.5.4 of this Chapter. The regional council, under its ‘Environmental Enhancement’ programme, has set ecological targets for protection of riparian margins in particular within the Tauranga Harbour and catchments, which mean increases to the extent, distribution and connectivity of riparian margins in the subregion. This replanting work programme has resulted in 28.92km of streams and harbour margins over the 2006/2007 period. At this rate, the overall goal is to retire and replant (with the aim of protecting), 80% by 2020 and 100% of the riparian margins by the year 2023, by current estimates. In addition to this, private landowners are also retiring marginal land which reverts into regenerating bush.

While the SmartGrowth projections and allocation for urban growth provides one scenario of land use change in itself, it also provides the underlying basis for developing the alternative land use change scenarios for this thesis, given that the various constraints for urban development allocation will also be applicable to any alternative urban growth scenarios. The most plausible variations to urban growth are likely to occur within areas already deemed suitable for urban development, but which have not been allocated to development under the current population projection for immigration into the subregion. Therefore, if higher immigration was assumed, another plausible alternative scenario is the ‘Build-out’ scenario (mentioned in Section 4.2), where urban development is allocated to its *maximum allowable extent* within the landscape, based on current factors for measuring suitability.

4.5.1 Urban Growth

Landcare Research has identified land that is classified as “severely constrained” and therefore generally unsuitable for urban development within the subregion (see Figure 4.6). This includes land that is flood-prone, steep, unstable, or subject to erosion. Development has generally been avoided in areas identified as "severely constrained". Some existing urban development is already located in constrained areas[34].

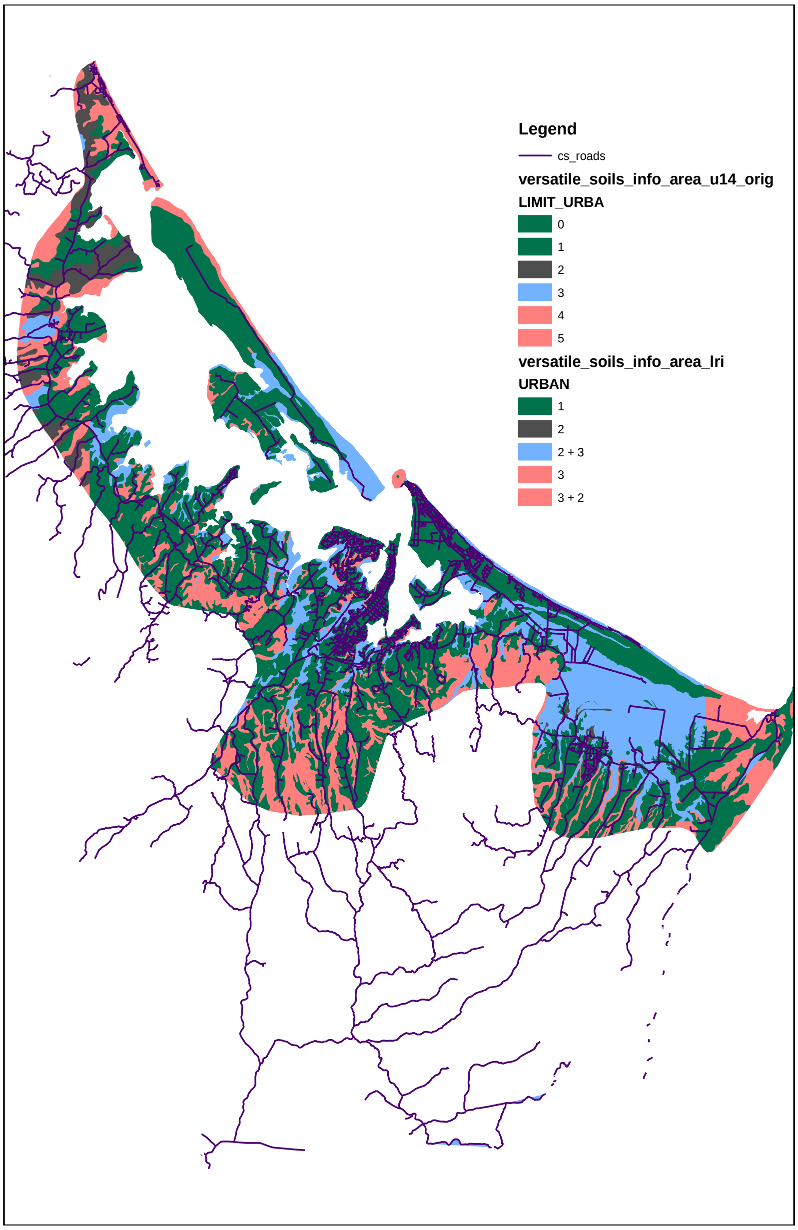

Figure 4.6 Urban constraints on future developments at the landscape-level also: 0-1 slight constraint; 2 moderate constraint; 3 severe constraint, with 2+3 and 3+2 being land classed as intermediate between classes 2 and 3. (GIS data provided by Environment Bay of Plenty).

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[34] Residential development is categorised into four broad types: Greenfield residential development (conversion of peri-urban agricultural land to urban areas), Intensification nodes (new or existing urban centres for planned intensification of built developments), General intensification and Papakainga.

A significant proportion of the land area within the sub-region (much of it already developed) has been identified as having low constraint, in landscape terms, for future urban development. Current planning controls focus only on significant and outstanding landscapes but growth is affecting other areas. The cultural view shafts from the 37 marae (Maori meeting places) within the sub-region reaffirm the direct relationships Tangata Whenua have with the environment and significant local taonga (things of importance). These sightlines also need to be taken into account into future settlement patterns.

There are a number of areas throughout the sub-region targeted for major development. Their planned roles are outlined in the following sections.

- Waihi Beach: Waihi Beach continues to operate predominantly as a beach holiday community serving Auckland, Waikato and the Bay of Plenty regions, with steady growth that results in more than a doubling of size by 2051.
- Katikati: Katikati Township retains its role as a rural service centre and increasingly becomes an alternative to high-density city-based lifestyles. It more than doubles by 2051, increased density providing additional capacity.
- Omokoroa: Omokoroa begins to develop after 2006. Omokoroa is recognised as a significant future growth area. (See Plate 4.1 for an aerial view of the Omokoroa peninsula and urban area).
- Bethlehem: Bethlehem continues to develop in line with existing zoned areas and structure planning. It reaches capacity by 2016.
- Pyes Pa: Additional land is developed at Pyes Pa after 2006. This is expected to reach capacity by 2031 and no further extensions within the planning period are intended. This takes into account the need to protect highly versatile land resources in this area.
- Welcome Bay and Ohauiti: Additional land is provided for residential development at Welcome Bay and Ohauiti after 2031, recognising the contribution made by the earlier development at Pyes Pa.
- Papamoa: There is on-going redevelopment at higher densities of increasingly sought after beachfront properties. The first part of Papamoa East (Wairakei) began development from 2007 and the second part (Te Tumu) between 2011 and 2016. Development of Te Tumu is contingent on resolving outstanding issues relating to land ownership and heritage and ecological values.
- Te Puke: Te Puke continues to grow steadily at current levels, limited in extent to protect highly versatile land and productive horticultural land. Nevertheless, population increases in size by 60% by 2051. (See Plate 4.2 Te Puke township).

Plate 4.1 The coastal settlement of Omokoroa which is scheduled for further staged urban growth (Source: http://www.westernbay.govt.nz/Your-district/ Western Bay of Plenty District Council, 2009, used with permission).

Plate 4.2 The settlement of Te Puke, one of the major horticultural areas of the Western Bay of Plenty (kiwifruit in particular). The highly versatile land surrounding Te Puke constrains the amount of future urban development likely to take place in this area (Source: http://www.westernbay.govt.nz/Your-district/ Western Bay of Plenty District Council, 2009, used with permission).

4.5.2 Ecological constraints to development

SmartGrowth supplied three categories of constraints to development:

1. *Highly constrained*: Indigenous vegetation and habitats – including harbours and protected areas.
2. *Moderately constrained*: Streams and riparian buffers; sites adjacent to indigenous vegetation and habitats, and harbours. Intensive development adjacent to natural areas will need to address threat-related issues set out above, and this may impose some limitations on the types of activities that should be allowed or encouraged in these areas. There are areas where it may be feasible to develop for residential housing but ecological issues will need to be addressed. There are areas that it may be feasible to develop for residential housing, but ecological issues need to be addressed. Examples of these are:
    - Plateaus inland of Te Puke.
    - Between Te Puke and SH33
    - Adjacent to and east of the Tauranga Direct Road.
3. *Not constrained*: Urban, pasture, industrial, commercial, horticulture, plantation forest outside of buffer zones adjacent to indigenous vegetation and habitats, and waterways.

Most flowing waterways should be protected, including riparian buffers. The width of riparian buffers will vary depending on the size of a waterway and associated topography. Small waterways could have riparian buffers 5-20 metres wide, while rivers (e.g. Wairoa) would warrant wider buffers. Waterways have been mapped as a constraint, and they should be addressed when development is being planned. Identification and protection of key ecological corridors is important. Priority is given to protection of the water quality and ecological and landscape values of Tauranga Harbour. This includes protection of stream corridors leading to the harbour.

Ecological constraints also exist in buffer zones adjacent to indigenous vegetation and habitats, including streams and harbours. The constraints will depend on the ecological values and issues associated with particular sites; e.g. domestic pets commonly travel 100-500 m, but the risk of unauthorised dumping of garden rubbish is greater within 200 m of natural areas. This is not to imply that no development should occur adjacent to indigenous vegetation and habitats, rather that there are ecological issues that need to be recognised and addressed for new development areas, such as domestic pets, invasive weeds, and other effects associated with the intensification of land use.

Areas with moderate natural character of the coastal environment include the balance of the marine area (i.e. the more developed areas around Tauranga City, Welcome Bay and Mt Maunganui). Two areas of visual significance as public view shafts are in the vicinity of the Minden and the top end f the harbour when travelling toward Tauranga from the Athenree Gorge. In these areas, more extensive forms of urbanisation, such a rural residential and rural lifestyle development, could be accommodated if careful consideration is given to their impact on the landscape attributes and values. In general, More intensive urban residential forms of development will not be appropriate unless they are constrained in pocket locations where there effects can be managed or they are of such a scale that their impacts are limited (e.g. small-scale resort development or rural residential cluster housing).

An increased emphasis is placed on the restoration of *degraded habitats* as a means of offsetting the impact of growth pressure. The priority areas for restoration of relevance to this study are: (1) harbour edge and freshwater wetlands; Wairoa, Kopurererua and Waimapu river valleys and (3) key ecological linkages along rivers and streams.

Thirty-five areas have high landscape constraint due to their outstanding natural features and landscapes. The whole of the Tauranga coastal marine area is also included, apart from the highly residential and industrial areas in Tauranga and around settlements in the Western Bay of Plenty (see Figure 4.7).

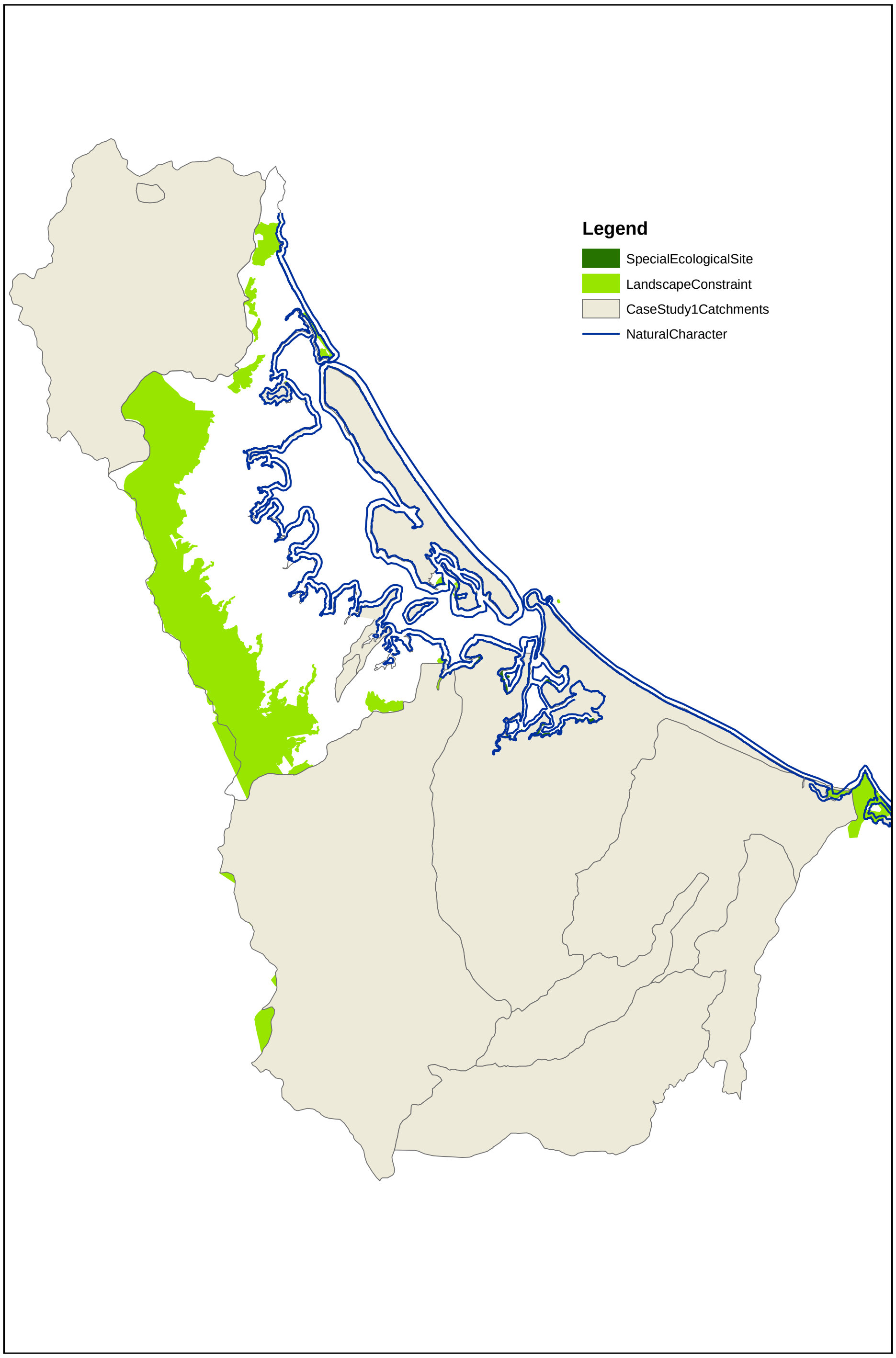
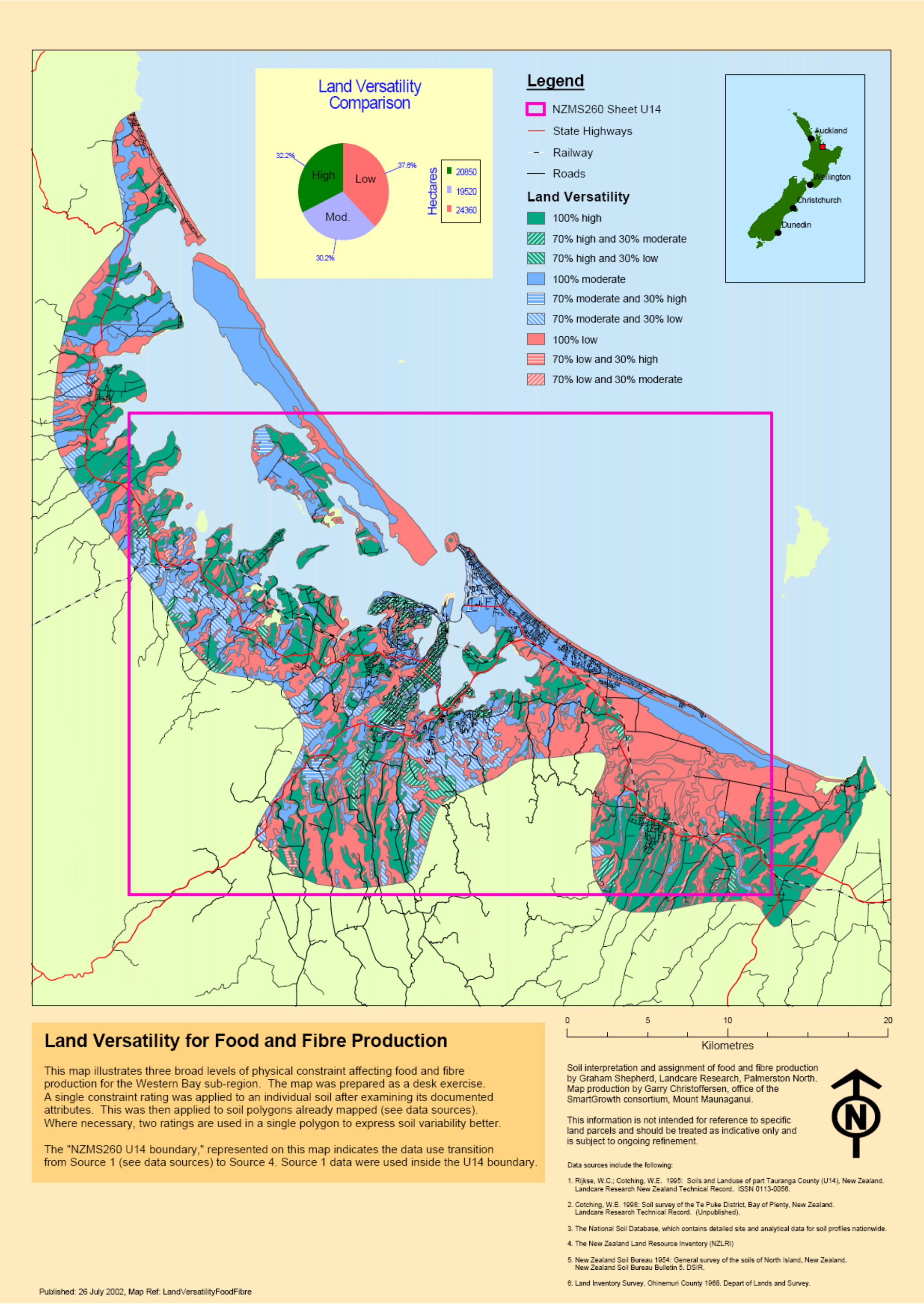


Figure 4.7 Landscapes and sites of ecological significance which both act as ecological constraints for urban development at the landscape-level (Data provided by Environment Bay of Plenty).

4.5.3 Highly Versatile Land

Land which has been identified as highly versatile for food and fibre production has been avoided where practicable. The choice of a compact urban form is driven partly by a community outcome that land with high versatility for production should be retained. Discussion with the community has reconfirmed the societal value of protecting land of high versatility. However, the policy of building on existing settlements means that some loss of land of this type will inevitably occur (See Plate 4.3 and Figure 4.8).

Plate 4.3 Horticultural land in the Western Bay of Plenty, showing an avocado orchard. Extensive horticultural areas are dispersed with the subregion and are an important part of the regional economy (Source: http://www.westernbay.govt.nz/Your-district/ Western Bay of Plenty District Council, 2009, used with permission).



Land Versatility for Food and Fibre Production

This map illustrates three broad levels of physical constraint affecting food and fibre production for the Western Bay sub-region. The map was prepared as a desk exercise. A single constraint rating was applied to an individual soil after examining its documented attributes. This was then applied to soil polygons already mapped (see data sources). Where necessary, two ratings are used in a single polygon to express soil variability better.

The "NZMS260 U14 boundary," represented on this map indicates the data use transition from Source 1 (see data sources) to Source 4. Source 1 data were used inside the U14 boundary.

Soil interpretation and assignment of food and fibre production by Graham Shepherd, Landcare Research, Palmerston North. Map production by Garry Christoffersen, office of the SmartGrowth consortium, Mount Maunganui.

This information is not intended for reference to specific land parcels and should be treated as indicative only and is subject to ongoing refinement.

Data sources include the following:

1. Rijkse, W.C.; Cotching, W.E. 1995: Soils and Landuse of part Tauranga County (U14), New Zealand. Landcare Research New Zealand Technical Record. ISSN 0113-0056.
2. Cotching, W.E. 1998: Soil survey of the Te Puke District, Bay of Plenty, New Zealand. Landcare Research Technical Record. (Unpublished).
3. The National Soil Database, which contains detailed site and analytical data for soil profiles nationwide.
4. The New Zealand Land Resource Inventory (NZLRI)
5. New Zealand Soil Bureau 1954: General survey of the soils of North Island, New Zealand. New Zealand Soil Bureau Bulletin 5. DSIR.
6. Land Inventory Survey, Ohinemuri County 1968. Depart of Lands and Survey.

Published: 26 July 2002, Map Ref: LandVersatilityFoodFibre

Figure 4.8 Highly versatile land for food and fibre production in the case study area. Land classed as having 'High' suitability for food and fibre production form a major constraint on urban development at the landscape-level (Source: Shepherd and Jessen, 2002, pg. 32, used with permission).

4.5.4 Rural Land

Rural areas are managed to provide for continuing rural production, resulting in gradual reduction in the supply of new sites for rural living. Around 5% of new residential development is expected to be accommodated in rural areas in 2051.

In the rural areas surrounding Tauranga City, a rural structure plan regime is implemented to provide better management of environmental and financial impact.

4.6 Developing LUC scenarios for the case study landscape

A scenario-based approach was chosen given that it is not the intention to provide predictive spatial modelling of land-use change, but rather to show a few alternative and plausible futures by which to test the sensitivity of landscape-level invasibility to land-use change. Given that the subregion is adopting a planned approach to urban growth (i.e. expanding disturbance); changes to native vegetation (i.e. habitats) and given the major focus of the subregion on riparian network restoration (and corridor connectivity), it was concluded that a 'process-based' forecast-type approach would be used to develop scenarios. This is because the assumptions, steps and events needed to reach alternative urban growth patterns (i.e. the SmartGrowth pattern, plus alternatives) are available through the SmartGrowth Strategy (e.g. population projections and trends, and assumptions, and ecological and land versatility constraints). Also, the local government authorities and other stakeholders are now committed to the SmartGrowth form of growth over the next 50 years and so this provides plausibility and legitimacy to building alternative scenarios that are primarily based on the various land use assumptions, though making variation to the projections for the extent and distribution of urban growth and replanting done in the subregion. In other words, to develop the alternative land use change scenarios at the landscape-level, In order to conceptualise land use changes that result in spatial changes to (1) *suitable habitat* (2) *sources of disturbance* and (3) *dispersal routes*, for *Tradescantia* at the landscape-level, a synoptic view of the broad drivers of change specific to the case study subregion and the invasion ecology of this species was necessary. A description of these drivers follows with a view to developing the ‘storylines’ used to create the individual ‘process-based’ scenario, hereafter named as: (1) the Baseline scenario; (2) the SmartGrowth Scenario; and (3) the Build-out scenario.

Changes to suitable habitat

Primary changes to the spatial distribution and extent of suitable habitats occur in two directions: habitat gains and habitat losses. Habitat gains in the case study area are occurring through regional and subregional biodiversity and environmental enhancement initiatives undertaken by the Environment Bay of Plenty, Queen Elizabeth II (QEII) Trust, and Nga Whenua Rahui, the Western Bay of Plenty, Tauranga City Council, Department of Conservation, and numerous other stakeholders in conjunction with private landowners. Losses occur primarily in the lowland areas as a result of vegetation clearance. All patches of suitable habitat in lowland areas are already vulnerable (by virtue of size, as illustrated in Chapter 2), so further vegetation clearance will only make it more vulnerable. Given that actual locations of vegetation clearance for suitable habitats not easily identified, on private land, we assume that the change to invasibility will be minimal, unless the area cleared causes a patch to be reduced in size from >9ha to <9ha. This sort of clearance is highly unlikely given that vegetation clearance is a discretionary activity in the subregion under the Bay of Plenty Regional Land and Water Plan, and is not encouraged.

Changes to disturbance: urban expansion

Disturbance changes over the time period to 2050, for the purpose of the scenarios, are linked primarily to the expansion of urban areas where urban stormwater and sewage discharges and associated increased nutrient and contaminant loading on urbanised streams, and degrading riparian vegetation along streams (Walsh et al., 2001 and Allan, 2004). Increased human presence also increases the chances that *Tradescantia* will be disposed off urban properties into adjacent or surrounding areas of natural vegetation. SmartGrowth and two other variations of it will be used to test the urban disturbance component.

Changes to dispersal pathways

Stream networks are not expected to change significantly over the time period to 2050 (though localised shifts in stream and river morphology may occur via natural mechanisms or through channelisation and other engineering works undertaken at the region-wide scale). It is expected that the change scenarios for dispersal will be related primarily to streams becoming a more effective dispersal route, as the number of *Tradescantia* infested sites in riparian habitats increases. Streams are likely therefore, to act as primary agents of dispersal that will aid in the persistence of disjunct metapopulations in the landscape.

4.6.1 Storylines for Land Use Change Scenarios

To produce the land use change scenarios based on the aforementioned habitat, disturbance and dispersal factors, four descriptive 'storylines' were developed to provide plausible alternative and qualitative futures, and are described in the next section. The following three descriptive storylines were developed in order to guide the development of the spatial land use change scenarios at the landscape-level.

4.6.1.1 Scenario 1: Baseline

The 'baseline' scenario presents land use in terms of suitable habitats (patches), disturbance sources (primarily urban and riparian areas) and dispersal sources (streams and roads) as they are currently (2008). This scenario is used as a measure of subsequent changes under the other three scenarios that were developed and assumes that no further land use change occurs. While it is temporally not plausible that there are no land use change after 2008, using this as a possible future scenario if mainly for the purpose of comparison of effects to the other scenarios, and for multiple comparison when integrated with other climate change scenarios in Chapter 6. In GIS the baseline scenario was produced by using three layers:

1. LCDBII Urban Class (Proximity to Urban was also calculated using Spatial Analyst);
2. Riparian network (ECOSAT dataset); and
3. Stream network (Proximity to streams was also calculated using Spatial Analyst).

Figure 4.9 shows the map that was produced.

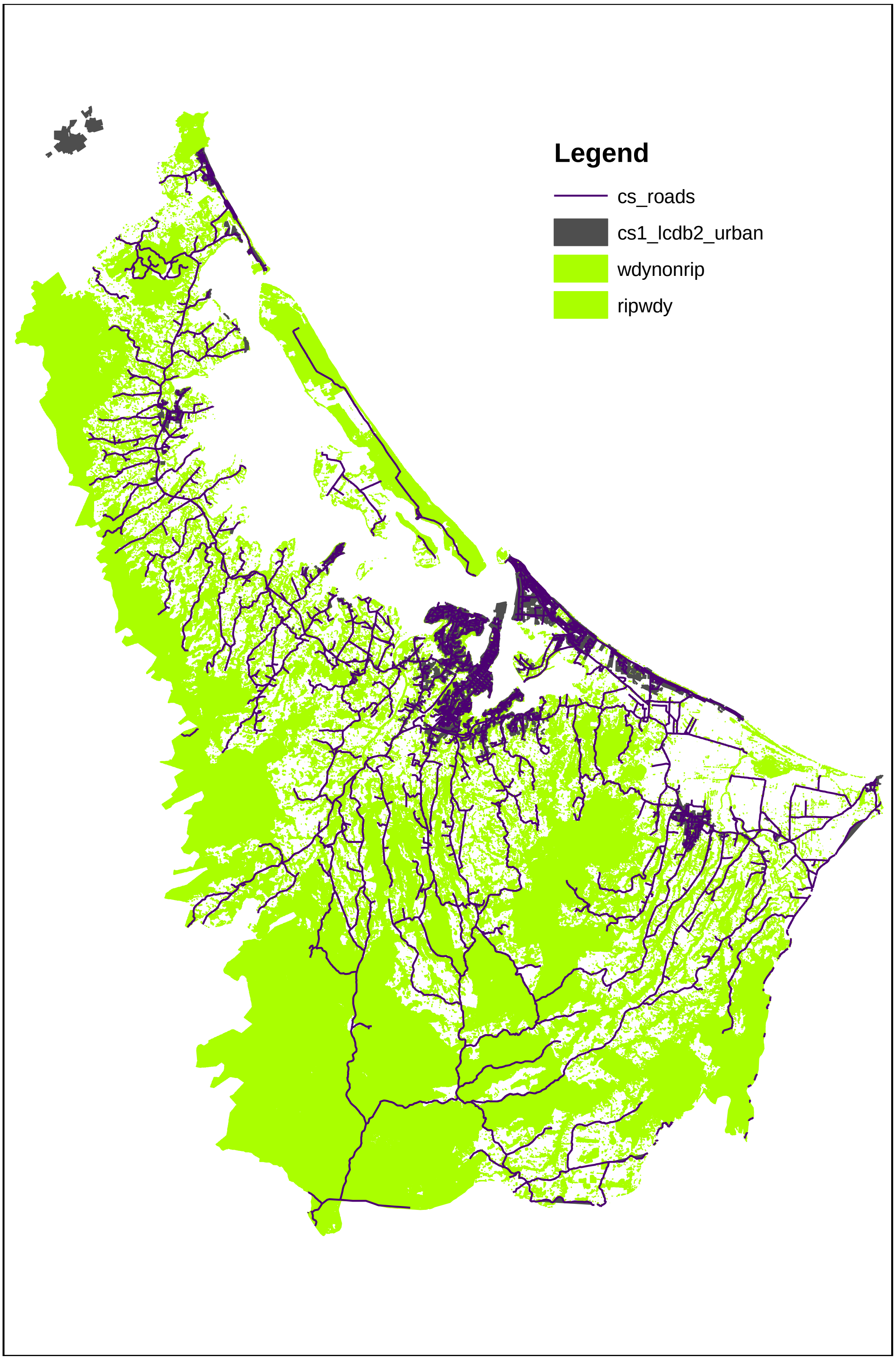


Figure 4.9 Baseline (no change) land use change scenario at the landscape-level. 'cs_roads' = the road network, 'Wdynonrip' = Woody non-riparian vegetation' and 'ripwdy' = riparian woody vegetation in all land use change scenarios (using the ECOSAT riparian data and road network layer, provided by Environment Bay of Plenty, and LCDB2-urban).

4.6.1.2 Scenario 2: SmartGrowth

Tests the change in land use to invasibility by *Tradescantia* using all SmartGrowth assumptions for population growth and urban ‘nodal’ intensification pattern for Papamoa, Pyes Pa, Welcome Bay and Ohauiti, Bethlehem, Te Puke, Omokoroa, Waihi Beach, and Katikati; with 100% riparian restoration and coastal buffers and specific areas being revegetated or buffered for environmental enhancement according the map of proposed areas for produced by the Environment Bay of Plenty. Outstanding features and landscapes are protected including areas of natural character with *only* areas of low natural character being targeted for growth.

In GIS the SmartGrowth scenario was produced by using three layers:

4. SmartGrowth Urban Areas + LCDBII Urban Class. Polygons from both layers were used to produce a new layer (a new Proximity to Urban was also calculated using Spatial Analyst);
5. Riparian network: All riparian classes were selected to produce a new layer in Spatial Analyst (using the ECOSAT dataset) representing 100% restored riparian margins; and
6. Stream network (Proximity to streams was also calculated using Spatial Analyst).

Figure 4.10 shows the resulting scenario spatially in GIS.

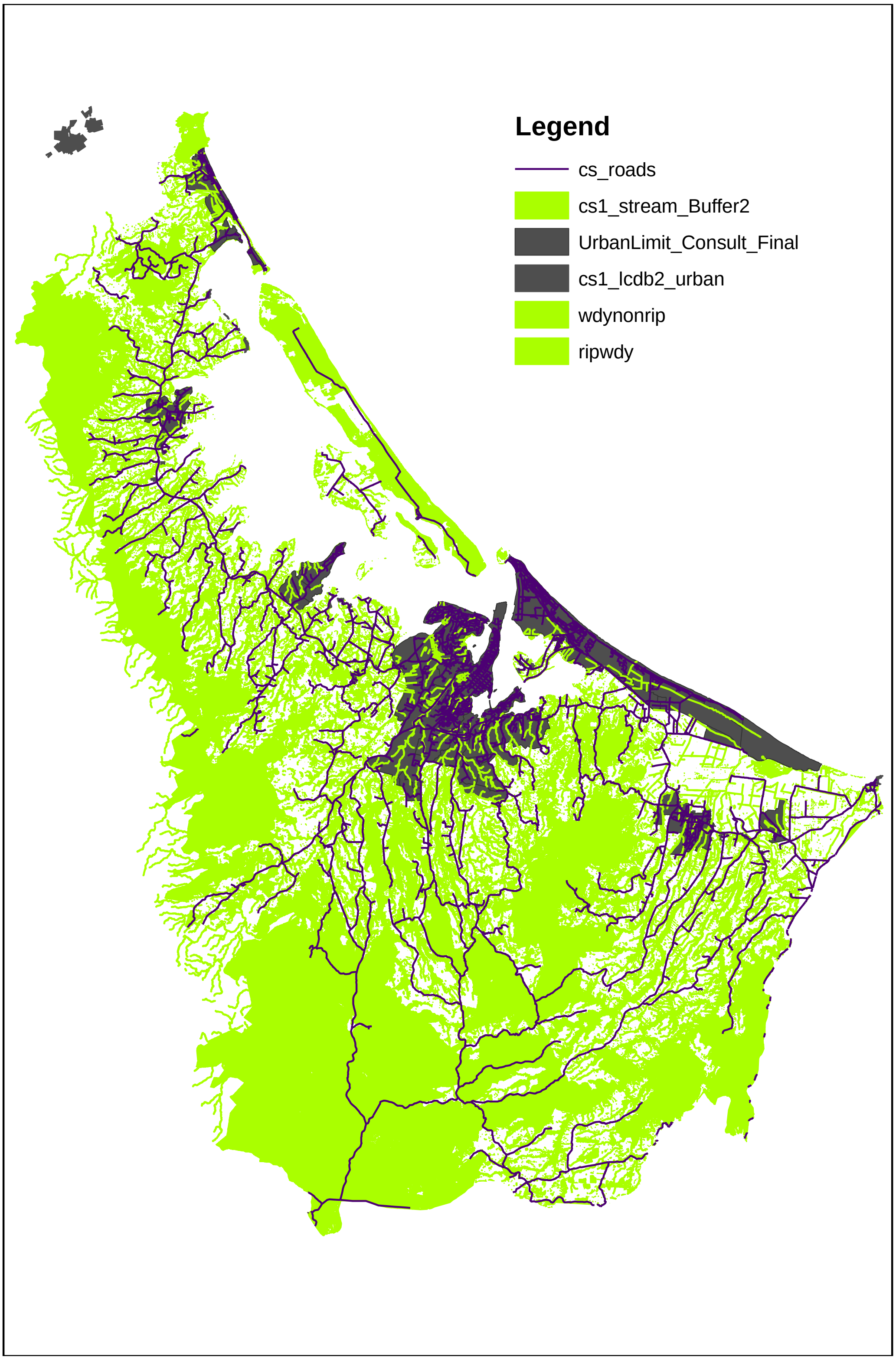


Figure 4.10 SmartGrowth land use change scenario at the landscape-level also incorporating changes to suitable habitats to 2050 (using the ECOSAT riparian data and road network layer, provided by Environment Bay of Plenty (modified), and SmartGrowth 2050 urban layer, provided by Environment Bay of Plenty).

4.6.1.3 Scenario 3: Build-out Growth

This scenario tests the change to invasibility from land use change, assuming a higher immigration rate than projected under SmartGrowth, such that the maximum allocatable land for urban development is used. To compensate for urban development impacts in the subregion, there is intensified restoration of riparian areas in particular in affected areas. The target to replant 100% of riparian margins is maintained. Outstanding features and landscapes are protected (though under more pressure from intensified development in the subregion), however areas of both low *and* moderate natural character are allocatable to urban development (so long as revegetation of riparian and other buffers are completed as a part of the impact mitigation process for each development).

In GIS the SmartGrowth scenario was produced by using three layers:

7. SmartGrowth Urban Areas + LCDBII Urban Class + All Low Slight and Moderately constrained areas for urban development (suitable but not allocated under SmartGrowth). Polygons from both layers were used to produce a new layer (a new Proximity to Urban was also calculated using Spatial Analyst);
8. Riparian network: All riparian classes were selected to produce a new layer in Spatial Analyst (using the ECOSAT dataset), however not all lowland riparian areas are restored due to the more intense pressure on urbanised streams (and their degradation, therefore representing 80% restored riparian margins; and
9. Stream network (Proximity to streams was also calculated using Spatial Analyst).

Figure 4.11 shows the resulting scenario spatially in GIS.

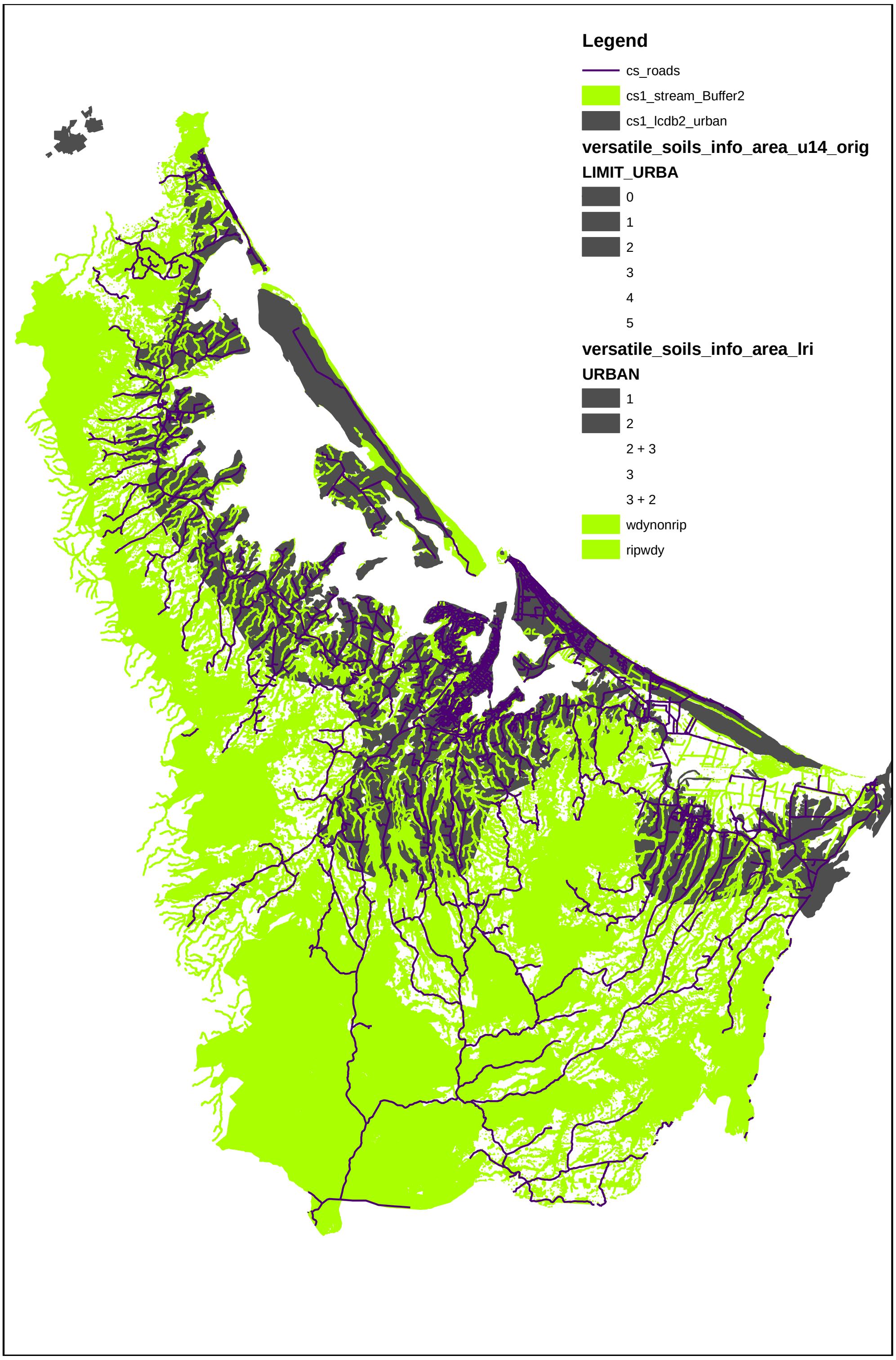


Figure 4.11 ‘Build-out’ land use change scenario at the landscape-level with ‘maximised urban settlement projections and also incorporating changes to suitable habitats to 2050. This impact of urban development is widespread across the landscape in this scenario (using the ECOSAT riparian data and road network layer, provided by Environment Bay of Plenty (modified), and Urban Constraint layer provided by Environment Bay of Plenty).

4.7 Assessing the LUC scenarios

The Western Bay of Plenty and Tauranga are projected to undergo significant land use changes over the period to 2050. In particular, two types of land use change are significant to *Tradescantia*'s invasion ecology and changes to its distribution in the subregion by 2050: (1) urban expansion and (2) biodiversity/environmental enhancement (via replanting and retiring riparian margins and retirement and associated increase in secondary vegetation on marginal lands.

Assessing the effects associated with these two types of land use change provides a context for assessing the changes to invasibility at the landscape-level with respect to *Tradescantia* and its future potential spread. Urban expansion has the effect of increasing the number and spatial extent of streams and remnant indigenous pockets of vegetation that are 'urbanised' and therefore subject to the degrading pressures that urban areas exert - increasing the disturbance level experience via new roads and tracks, stormwater inputs, erosion, soil and vegetation disturbance and nutrient inputs. These disturbances also aid in mobilising propagules from existing sites within these newly urbanised areas. Biodiversity/environmental enhancement will extend the number and area covered in indigenous vegetation, particularly expanding the area under indigenous vegetation in the riparian network. Replanting/retiring the riparian network has the effect of providing suitable habitat for *Tradescantia*, given that many existing patches of riparian vegetation in the subregion are already invaded by *Tradescantia*. These existing populations act as source populations for establishing sink populations further downstream in newly revegetated habitats.

Under the 'Baseline scenarios' the extent of urban areas and riparian and non-riparian habitats stay the same, and this provides a scenario against which to compare other scenarios. The 'SmartGrowth Scenario' results in an overall increase of indigenous vegetation through environmental enhancement work, which provides potential suitable habitat for *Tradescantia* and its metapopulation persistence in the landscape, given that stream will be effective conduits for short, medium and long distance dispersal for this species. Riparian replanting also has the effect of increasing the connectivity of suitable habitats at the landscape-level. This would have the effect on *Tradescantia*, of providing a more continuous corridor of suitable habitat through which to mobilising propagules and establish new satellite populations. Under this scenario, urbanisation is allocated to its maximal level of suitability, and presents a more extreme case of urban pressure on the landscape. The improved connectivity of the riparian margins, coupled with the more extensive pressure on urbanised streams and remnant vegetation, in downstream lowland areas, means that *Tradescantia* in its localised population is likely to be most disturbed in this scenario.

4.8 Summary

Three alternative scenarios for land use change were produced in this Chapter including: (1) the Baseline scenario (no change scenario); (2) the 'SmartGrowth Scenario' and (3) Build-out Scenario'. These land use change scenarios were created in a GIS using spatial information developed as a part of the subregional strategic planning process, SmartGrowth, within the Western Bay of Plenty and Tauranga, with a time horizon to 2050. These scenarios are based on land use constraints such as: soil characteristics that affect suitability for urban development, ecological, landscape, character and land versatility for food and fibre production constraints. Since there was such an explicit spatial planning process under way in the subregion, and a commitment to its spatial constraints on allocating development, as well as extensive efforts to meet revegetation targets of fully replanting riparian margins before the year 2050, these constraints and policy-level targets were utilised in developing the spatial scenarios.

Under all scenarios, the amount of suitable habitat increases for *Tradescantia* and the level of urban disturbance to streams and remnant vegetation also increases. This has the projected effect of making the landscape more suitable for *Tradescantia*'s continued spread and persistence, mainly because riparian connectivity in improved, allowing for more effective establishment and continued water-aided dispersal for short to longer distances.

5 Chapter 5: Climate change scenarios

5.1 Introduction

This chapter produces the spatially explicit scenarios of climatic change to assess potential spatial distribution changes for *Tradescantia fluminensis*. In Chapter 4, the development of land use change scenarios for the Western Bay of Plenty and Tauranga for species distribution modelling was addressed. These integrated scenarios will be used to conduct an analysis of future changes in the distribution of *Tradescantia* in Chapter 6, using the Ecological Niche Factor Analysis (ENFA). Climate change scenarios are defined, methods for creating them are reviewed and scenarios are created at two scales: national and regional, using the CLIMPACTS Open Framework Modelling System.

The climate of New Zealand is projected to change discernibly over the 21st century. The IPCC 2007a AR4 Report states that in New Zealand, a warming of 0.1 to 1.4°C is likely by the 2030s and 0.2 to 4.0°C by the 2080s. There is projected to be an increase in the annual mean westerly component of windflow across New Zealand and by 2090 this could mean a > 50% increase in winter (MfE, 2008). As a result, it is expected that precipitation is likely to increase in most parts of the country, except in the eastern North Island and the northern South Island. There is likely to be a shortened duration of snow lying, rise in snowline and a decrease in snowfall events (MfE, 2008). The overall projections are for a decrease in frost frequencies, for instance, by 2100, there is likely to be a 5 to 20 day decrease in frosts in the lower North Island, and 10 to 30 fewer frost days in the South Island, and a 5 to 70 day increase in the number of days with temperatures over 30°C (Mullan et al., 2001). The frequency of heavy rainfall is likely to increase, especially in western areas (MfE, 2008).

The development of spatially-explicit climate change scenarios that portray the projected changes in climatic variables is essential in undertaking integrated assessments, where the objective is to test the sensitivity of the system of interest to the spatio-temporal changes - for instance the sensitivity of: individual species, terrestrial and marine ecosystems, agricultural and horticultural sectors, and coastal infrastructure (Izaurralde et al., 2003; IPCC, 2001; Kenny et al., 2000, and 2001; Warrick et al., 1996).

5.2 Climate scenarios

The IPCC 2007 AR4 report as well as the TAR[35] define a *climate scenario* as:

> "A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate."

A *climate change scenario* refers strictly to a representation of the difference between some plausible future climate and the current or baseline climate (usually represented in a climate model). Scenarios are not considered to be either predictions or forecasts of future conditions (IPCC, 2001). Instead they are descriptions of alternative plausible futures that conform to sets of circumstances or constraints within which they occur (Hammond, 1998). A distinction is made between climate scenarios, which describe the forcing factor of focal interest to the IPCC, and non-climatic scenarios, which provide the socioeconomic and environmental context within which climate forcing operates (for instance land use change scenarios). Most assessments of the impacts of future climate change are based on results from impact models that rely on quantitative climate and non-climatic scenarios as inputs (Smith et al., 1998).

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[35] TAR- Third Assessment Report of the International Panel on Climate Change (IPCC, 2001).

5.3 Approaches to climate scenario development

Three main types of climate scenarios are employed in impact assessments: (1) incremental scenarios (2) analog scenarios and (3) model-based scenarios. The methods outlined here are mainly based on the scenario development outlined in the IPCC 2001 WGII Report and by Smith et al. (1998) as both are referred to widely in climate change scenario development literature.

'Incremental scenarios' are simple adjustments of the baseline climate according to anticipated future changes that can offer a valuable aid for testing system sensitivity to climate. They have been reported from several earlier studies (Dvorak et al., 1997; Jaagus, 1997; and Smith and Pitts, 1997). However, because they involve arbitrary adjustments, they may not be realistic meteorologically, or for assessing changes at specific temporal periods. As a result, while these scenarios are seen to be useful in assessing the sensitivity of a system they are not particularly useful when assessing changes to climate in a time-dependent manner.

'Analog scenarios' represent changed climate from the past record or from other regions. A few early studies used analogue scenarios for exploring impacts of climate changes, however, these were usually in combination with model-based Global Climate Models (GCMs) (for example Smith and Pitts, 1997). Climate analogues may be difficult to identify, particularly if historical analogues are the objective. Analogue scenarios are seldom applied, although they sometimes can provide useful insights into impacts of climate conditions outside the present-day range.

'Model-based scenarios' are the most commonly applied scenarios in climate change assessments, and are based on outputs from Global Climate Models (GCMs), usually constructed by adjusting a baseline climate (typically based on regional observations of climate over a reference period such as 1961-1990), by the absolute or proportional change between the simulated present and future climates. The most advanced Global Climate Models couple atmosphere and ocean models and are referred to as coupled Atmosphere-Ocean General

Circulation Models (AOGCMs) (Mearns et al., 2003; IPCC, 2001; and Smith et al., 1998).

AOGCMs are mathematical representations of atmosphere, ocean, ice cap, and land surface processes based on physical laws and physically-based empirical relationships. Such models have been used to examine the impacts of increased greenhouse gas concentrations on future climate (Sokolov et al., 2003; Raper et al, 2002; and Giorgi and Francisco, 2000). The typical AOGCM is a time-dependent, transient experiment. Here a coupled GCM is used to simulate current ($1xCO_2$) climate (i.e. a 'control run') and then future climate (i.e. a 'perturbed run') as it responds to changes in greenhouse gas concentrations over time (e.g. Mearns et al., 2003; Raper et al., 2002; Gregory et al., 2001; Giorgi and Francisco, 2000; and Manabe and Stouffer, 1995). A typical forcing scenario in a transient experiment is a 1 percent per year increase in CO_2 concentration, but many different forcing scenarios have been used. The model is typically run for 100 years or more into the future.

Impact studies (since the mid-1990s) have constructed scenarios on the basis of transient AOGCMs, although some still apply earlier equilibrium results. The results of many of these AOGCM simulations have been put together in the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre (DDC) dataset (http://ipcc-ddc.cru.uea.ac.uk) and show a range of global mean temperature change and ocean thermal expansion by the end of the twenty-first century (Raper et al., 2001).

The major advantage of using AOGCMs as the basis for creating climate change scenarios is that they are the only tool that estimates changes in climate due to increased greenhouse gases in three dimensions (latitude, longitude and altitude), for a large number of climate variables in a physically consistent manner.[36] It is

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[36] Although the variables within a GCM are all determined using physical laws, or empirical relationships based on physical laws, validation studies show that the internal relationships between these model variables may not necessarily be the same as the relationships observed in the

also the only approach that can produce regional scenarios. The GCMs estimate changes in a host of meteorological variables, e.g., temperature, precipitation, pressure, wind (Giorgi and Francisco, 2000; Giogi and Mearns, 2002; Pryor, Schoof and Barthelmie, 2005), that are consistent with each other within a region and around the world. As a result, AOGCMs were selected as the most appropriate model-based scenario approach to use in this thesis.

Incremental and analogue scenarios were not chosen given that incremental scenarios are often meteorologically unrealistic and are based on arbitrary adjustments of CO_2 concentrations (and also one is not able to say for which time in the future it applies); while analogue scenarios are not used because it is not easy to identify adequate climatological analogues for New Zealand (given the wide latitudinal range).

For further background theory on the development of spatially-explicit scenarios of climate change, based on the IPCC methodologies, refer to Appendix 5. Its application to this thesis is addressed in Section 5.2. The following section describes some of the sources of uncertainty associated with climate scenarios, and various methods in use to quantify and characterise the uncertainty in integrated assessments of climate change.

5.4 Addressing uncertainties in climate scenarios

The concept of uncertainty is implicit in the development of climate scenario, and therefore, characterisation and quantification of uncertainty has become one of the most important branches of climate scenario research. Some important sources of uncertainty are detailed in TAR WGI Chapter 13, of which some of the major sources are:

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real world. This is because of deficiencies in the GCM (Smith et al., In Feenstra et al., 1998).

1. Uncertainties in future greenhouse gas (GHG) and aerosol emissions;
2. Uncertainties in converting emissions to GHG concentrations;
3. Uncertainties in converting concentrations to radiative forcing[37];
4. Uncertainties in global climate sensitivity[38], mainly as a result of differences in the way physical processes and feedbacks are simulated in different models. This means that some GCMs simulate greater mean global warming per unit of radiative forcing than others;
5. Uncertainties in converting model response into inputs for impact assessment;
6. Uncertainties in regional climate changes, which are apparent from differences in regional estimates of climate change by different GCMs for the same mean global warming.

Many early impact studies employed a climate scenario derived from a single GCM. However, it was recognized early on that different GCMs yield different regional climate responses, even when they are perturbed with identical forcing (e.g., Smith and Tirpak, 1989). Therefore, various approaches have been used to capture this range of responses in impact studies. These approaches include using a selected subset of GCM experiments, in some cases based on the performance of the GCMs at simulating the current climate (e.g., Risbey and Stone, 1996) or results from different GCMs that have been "pattern-scaled" in conjunction with

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[37] Radiative forcing, as defined by the IPCC WGI, is: “the change in the net, downward minus upward, irradiance (expressed in W m–2) at the ‘tropopause’ (the boundary between the two atmosphere layers: the troposphere and the stratosphere) due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun. Radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called *instantaneous* if no change in stratospheric temperature is accounted for. For the purposes of this report, radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value. Radiative forcing is not to be confused with *cloud* radiative forcing, a similar terminology for describing an unrelated measure of the impact of clouds on the irradiance at the top of the atmosphere” (IPCC, 2001).

[38] “In IPCC Reports, equilibrium climate sensitivity refers to the equilibrium change in global mean surface temperature following a doubling of the atmospheric (equivalent) CO_2 concentration. More generally, equilibrium climate sensitivity refers to the equilibrium change in surface air temperature following a unit change in radiative forcing (°C/Wm^{-2}). In practice, the evaluation of the equilibrium climate sensitivity requires very long simulations with Coupled General Circulation Models (Climate model). The effective climate sensitivity is a related measure that circumvents this requirement. It is evaluated from model output for evolving non-equilibrium conditions. It is a measure of the strengths of the feedbacks at a particular time and may vary with forcing history and climate state” (IPCC, 2001).

simple climate models to represent different types of uncertainty (e.g., Barrow et al., 2000).

GCM simulation results are likely to capture a large part of the uncertainty ranges in points 4) and 5), however, they do not include the ranges of uncertainties in 1)-3). Due to time and resource constraints only a limited number of GCM experiments can be conducted. However, for plausible assessments of the risk of climate change in impact and adaptation studies, the range of scenarios and type of approaches used will depend on the research approach used (Dessai et al., 2005).

A convenient solution to the relative scarcity of GCM experiments that sample the range of climate projection uncertainties caused by different emissions scenarios is to use pattern-scaling techniques. Pattern-scaling techniques are now in use as a low cost alternative to expensive AOGCM and RCM experiments. This approach involves normalizing temperature change. These normalized patterns are then rescaled using scalar (global mean temperature change, ΔTg) derived from simple climate models (e.g. MAGICC) and representing the particular emissions scenario under construction (Mitchell, 2003). The theoretical assumption is that there is a linear relationship between the scalar variable (for example mean annual temperature) and the response pattern derived from the pattern-scaling (Mitchell, 2003). Mitchell (2003) suggests that pattern scaling enables an accurate estimate to be made of the regional climate changes that would be simulated by a GCM under different radiative forcings and facilitates a probabilistic approach to the assessment of future regional climate change.

In the following sections, climate and climate change scenarios will be generated using multiple AOGCMs, SRES scenarios for greenhouse gas and aerosol emissions and at three climate sensitivities at the national (New Zealand) and regional (Bay of Plenty) spatial scales. These scenarios were produced within the CLIMPACTS Open Framework System. At both scales the resulting climate and climate change scenarios were produced at a 100m spatial resolution. The regional scenarios were further resampled at a 15m resolution in order to integrate these climate layers with the other habitat and landscape level invasibility layers produced in Chapters 2-4.

5.5 Generating climate scenarios using the CLIMPACTS Open Framework System

The CLIMPACTS Open Framework System was selected for generating the climate change scenarios because it contains the climatology layers (both national and regional) for New Zealand, along with the climate change patterns. It was specifically designed for assessing the impacts of climate change in the New Zealand context, and has subsequently also been developed into a generic software system known as SimCLIM. This modelling framework is flexible and enables it to be easily adapted to any region in the world and to be designed for sensitivity studies of any climate change related issue (Warrick et al., 1996; 2001; Kenny et al., 1995; 2000).

CLIMPACTS is a computer-based integrated system that combines models and data sets for the purpose of undertaking climate change impact assessments for New Zealand. The original CLIMPACTS model was used to assess three sectors: natural vegetation (tree species), agriculture (grasslands and arable crops), and horticulture (kiwifruit). Many of its variants have been developed and used in parts of the world for a similar use - to conduct impact assessments of climate change focusing on selected sectors (Warrick, in press). These variants were reproduced with a similar concept and with the core code of the CLIMPACTS model. The key aspects of this family of models are simplicity and flexibility. The models can also be adapted quickly to follow developments in climate change science.

The conceptual structure of the CLIMPACTS Open Framework System consists of several models and analytical tools, which can be divided into two main stages (Figure 5.1). The first stage is a ‘scenario generator’ and the second stage consists of ‘sectoral models’. The scenario generator component comprises a global climate model which links with a regional climate change scenario generator. The regional climate change is derived by bringing together: all historical climate data (temperature and rainfall) for baseline construction; patterns of climate change from GCMs; and temperature and sea-level change patterns which are the output of the global climate model. They are processed in the regional climate change scenario generator. For the purpose of this thesis, the CLIMPACTS system will be used primarily to generate the climate and climate change scenarios, which are subsequently imported into BioMapper to perform the Ecological Niche Factor Analysis, for the species distribution modelling.

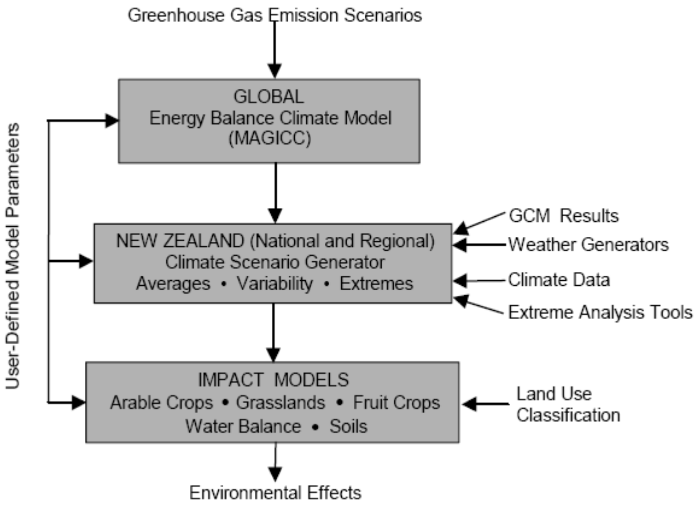

Figure 5.1 Conceptual structure of the CLIMPACTS Open Framework System. The CLIMPACTS software used to generate the climate and climate change scenarios for the study. (Source: Warrick et al., 2001).

The global climate model used in CLIMPACTS is MAGICC (Model for Assessment of Greenhouse gas Induced Climate Change). It is classified as a simple climate model (Wigley, 2005) and can be used to generate time-dependent global temperature and sea-level change induced by the emission of GHGs (New and Hulme, 2000; and Dessai and Hulme, 2001). The current variant of CLIMPACTS uses the IPCC SRES marker scenarios (A1, A2, B1, B2 storylines families) (IPCC, 2000). Sections 5.2.1 to 5.2.5 describe the steps undertaken to produce the spatial scenarios.

5.5.1 Baseline climatology

A climate scenario must have a reference *baseline period* from which to calculate changes in climate. This baseline data set characterizes the sensitivity of the exposure unit to present-day climate and usually serves as the base on which data sets that represent climate change are constructed. Among the possible criteria for selecting the baseline period, it should be representative of the present-day or recent average climate in the study region and of a sufficient duration to encompass a range of climatic variations, including several significant weather anomalies (e.g., severe droughts or cool seasons) (IPCC, 1994 in IPCC, 2001). The most popular climatological baseline period is a 30-year "normal" period, as defined by the World Meteorological Organization (WMO). The current WMO normal period is 1961-1990, which provides a standard reference for many impact studies (e.g. Kenny et al., 1995; Hulme et al., 2000; IPCC 2001). The period 1960-1990 was selected as the baseline for this study.

5.5.2 Selecting climate variables

For CLIMPACTS, the climate data sets used were from the Land Environments New Zealand (LENZ) developed used interpolated data sets, produced by Manaaki Whenua Landcare Research in New Zealand. These national data sets were then used to produce regional-scale climate surfaces for temperature and rainfall variables, and were available at a 100m spatial resolution. For this study, the data sets consist of the Mean Minimum Temperature for July-August, MTminJ-A, and Annual Water Deficit (AWD). It was envisaged that these variables were likely to spatially characterise areas as climatically unsuitable, marginal or suitable for *Tradescantia*, given that they represent extremely cold and extremely dry climatic conditions. Based on the species-environment relationships explored in Chapter 2, it is likely that the future scenarios of these variables would show the sensitivity of *Tradescantia's* distribution to changes in the extremely cold and extremely dry areas, hence providing information, in the first instance, on changes to areas that change from being climatically unsuitable to marginal or suitable.

For this study the primary variable of interest was: MTminJ-A, that closely approximated the national distribution and hence climatic suitability for *Tradescantia* in New Zealand. Precipitation (*P*), Water balance (or associated AWD) were also meaningful variables, though to a lesser extent, given that precipitation is more spatially stochastic and most areas in New Zealand would have zero or low values for water deficit (as explained in the species-environment relationships analysis in Chapter 2).

Therefore, climate and climate change scenarios were generated for (1) TminJ-A and (2) Potential Evapo-transpiration, PET. PET was then converted to annual water deficit to match the annual water deficit variable used in Chapters 2 and 3, developed by Landcare Research.

5.5.3 Selecting GCMs

There were several options with regard to GCM patterns to be used. Within CLIMPACTS the following GCMs were available at the national level for MTminJ-A and PET: Canadian Climate Centre (CCC), the Japanese Centre for Climate Study Research (CCSR), the CSIRO4 and CSIRO9 from the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the HadCM3 from the U.K. Hadley Centre for Climate Prediction and Research. At the regional level, the following GCMs were available: Darlam (named from CSIRO Division of Atmospheric Research Limited Area Model) comes from a double nesting of a limited area high resolution model into the CSIRO9-level

GCM. It is the only example for New Zealand, of a climate change scenario generated from a high resolution regional climate model nested within a GCM (Renwick et al., 1998). Additionally, the Darlam and U.S. Geophysical Fluid Dynamics Laboratory (GFDLQ) high resolution models were available at the national level for the PET variable scenario generation only. Four of the GCMs on the IPCC Data Distribution site (where the GCM patterns are downloaded from for CLIMPACTS), provide simulations through to the year 2099: CCC, CCSR, CSIRO9 and HadCM3. These GCMs along with the Darlam GCM, at the regional level, were selected for the scenario development (as per the GCM selection in the CLIMPACTS assessment, Mullan 2001). The CCC, HadCM2 and HadCM3 and CSIRO GCMs are widely used in the assessment of climate change impacts and have been used with relation to impacts on species for biodiversity and conservation-type assessments (Araujo et al., 2004; Peterson et al., 2004; Thuiller, 2004; Midgley et al., 2002; Berry et al., 2002; and Iverson and Prasad, 2002). Therefore, the choice of these GCMs seemed a valid one. Further to this, Section 5.2.6 describes the comparison between GCM outputs used to determine the number of GCMs used within this study.

5.5.4 Selecting greenhouse gas emissions scenarios

The IPCC Special Report on Emissions Scenarios (SRES) in replacing the IS92 scenarios used previously in climate change modeling, identifies 40 different scenarios in following four families of possible global futures, or story-lines (A1, A2, B1, and B2) with associated radiative forcing increases ranging from 0.4% to 1.2% per year (IPCC, 2000). The probability for each of the scenarios is equal. Table 5.1 illustrates the major groupings of the SRES scenarios Families while Figure 5.2 groups the SRES scenarios according to: Storyline, Family, and Groups. These scenarios are based on the underlying driving forces of greenhouse gas and aerosol emissions represented in the literature.

SRES Family	**SRES Storyline**
A1	The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: A1F1: fossil intensive A1T: non-fossil energy sources, or A1B: a balance across all sources
A2	The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.
B1	The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
B2	The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Table 5.1 The SRES Storylines and Scenario families. The broad economic, population, and technological changes are described for four main families: A1, A2, B1, and B2 (Source: IPCC, 2000, used with permission).

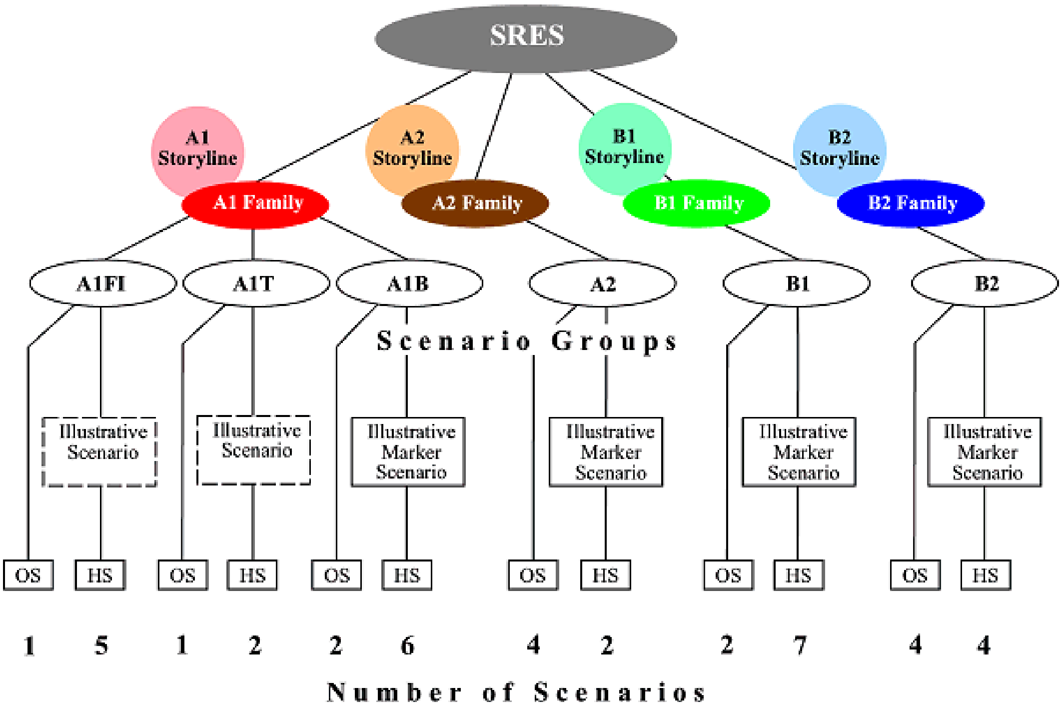

Figure 5.2 Schematic of the grouping The SRES Emission Scenarios. The scenarios were developed. by the Nakicenovic et al., 2000, showing the 4 main storylines A1, A2, B1, B2 and their corresponding families of scenario groups used to develop the projected future climates and climate change scenarios (Source: IPCC, 2000, used with permission).

There are no SRES scenarios which include possible greenhouse gas emissions reductions as a result of the implementation of the United National Framework Convention for Climate Change (UNFCCC)[39] or the emissions targets of the Kyoto Protocol[40].

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[39] The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. It contains commitments for all Parties.

Under the Convention, Parties included in Annex I (all OECD countries and countries with economies in transition) aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The convention entered in force in March 1994 (IPCC, 2001).

[40] The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1997 in Kyoto, Japan, at the Third Session of the Conference of the Parties (COP) to the UNFCCC. It contains legally binding commitments, in addition to those

In this study, more than one emissions scenarios were used in combination with the selected GCMs in order to account for the different possible outcomes across various SRES socio-economic storylines (for example: Araújo et al., 2006; Schröter et al., 2005; Peterson et al., 2004 and Thuiller, 2003). This is further described in Section 5.5.6. The following section provides the background to the technique of pattern scaling which is essential to producing the regional climate scenarios from downscaled GCM patterns, introduced in Section 5.1.4.

5.5.5 Downscaling GCMs to regional levels

Using statistical downscaling of transient AOGCMs, Mullan et al. (2001) produced future climate projections for New Zealand. The projections were downscaled because orographic changes distort the global-scale GCM pattern over the New Zealand land mass. The downscaling was based on regression relationships between the GCM pattern and long-term time series data from New Zealand climate stations (Mullan, 2001). Simulations by six AOGCMs were used, all having a common “1%/annum compounding CO_2 plus sulphate” emissions scenario. This was similar to the mid-range IPCC scenario referred to as SRES A1. The projections were applied to two future 30-year ‘climatological’ periods 2020–2049 (referred to as the ‘2030s’ in brief) and 2070–2099 (‘2080s’) (MfE, 2004).

The New Zealand downscaled changes of Mullan et al. (2001), for all models, adjust the climate projections for 1990, as per IPCC practice. Hence the projections are multiplied by factors 0.509 to 1.104 (both the lower and upper limits) for the 2030s and 0.546 to 1.567 for the 2080s. The changes were ranked, and the extreme low and high values extracted. The resulting range was termed

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included in the UNFCCC. Countries included in Annex B of the Protocol (most Organisation for Economic Cooperation and Development countries and countries with economies in transition) agreed to reduce their anthropogenic greenhouse gas emissions (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride) by at least 5% below 1990 levels in the commitment period 2008 to 2012. The Kyoto Protocol entered into force on 16 February 2005 (IPCC, 2001).

the ‘full’ or ‘robust’ IPCC range for New Zealand. This approach of scaling local changes by changes in global temperature is a common way of deriving local changes in the absence of climate model simulations (from actual GCM experiment runs) with the desired emission scenario. One difficulty with this method is that model changes at the regional level are quite often not linear with respect to the global average temperature change (MfE, 2004).

5.5.6 Generating scenarios in the CLIMPACTS system

5.5.6.1National level: Minimum temperature (July-August) scenarios

The climate change scenarios were generated in the CLIMPACTS system, using the ‘Scenario Generator’ tool. Scenarios were generated for the north and south island levels separately; and then at the regional level. The regional scenarios (for the Bay of Plenty and all other regions in New Zealand) were created by a linear interpolation of the downscaled GCM pattern, in order to increase the spatial resolution of the scenarios to 100m, so that they can be integrated with the Land Environments of New Zealand (LENZ) for further regional integrated impacts assessments.

There are two types of scenarios that can be generated: synthetic and linked model (or model based). The most commonly used approach for developing scenarios in the CLIMPACTS system involves the scaling of the standardised, downscaled patterns of climate change for New Zealand (developed by Mullan et al., 2001 and described in Section 5.5.2), with the time-dependent projections of global-mean temperature change[41]- a ‘linked-model approach’ (Gregory et al., 1997). These changes are used to perturb the present climate (the 1990 baseline) and hence

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[41] This uses the global warming trend from the IPCC Special Report on Emissions Scenarios (SRES) series. The global model used to generate the global trend is the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC). The projected trends include Atmospheric CO2 concentration, temperature, total sea level change and thermal expansion caused sea level change. Projections are made from the baseline (starting in 1990) until 2100. Each projected trend has a range of low, best guess, and high value corresponding to the uncertainty related to GHG emission scenarios.

create climate scenarios for the year of interest (e.g. 2050). Therefore, within CLIMPACTS the following calculations are made to produce the final spatial climate scenarios for temperature and rainfall:

Equation 1:

Future temperature = Present temperature + (MAGICC value x Standardised GCM pattern of temperature change, in °C)

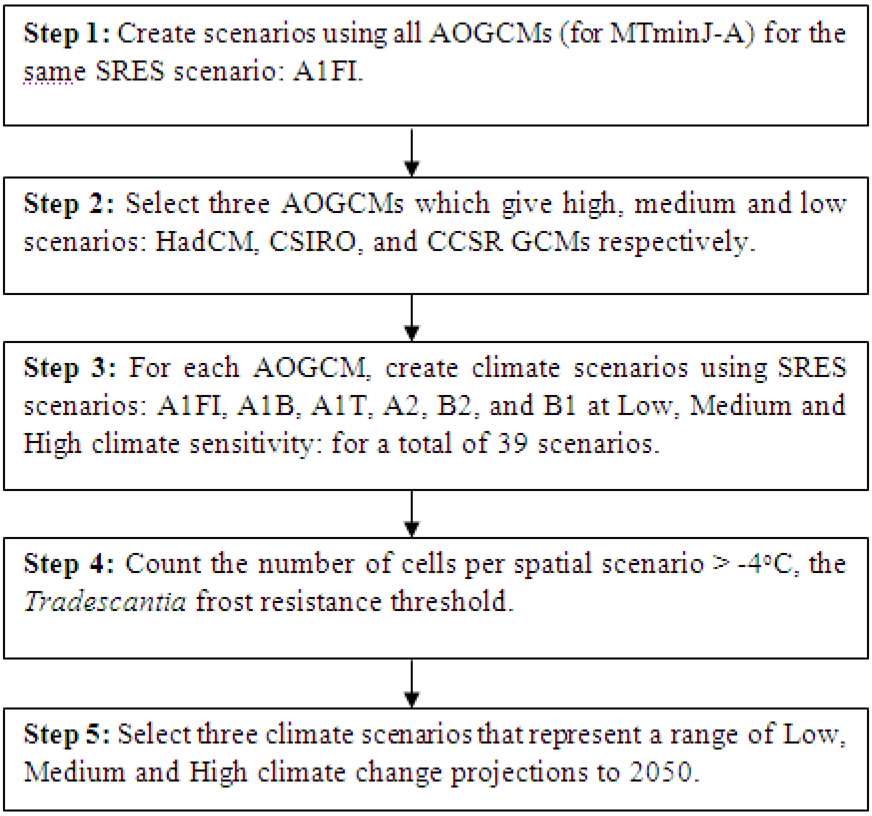
Equation 2:

Future precipitation = Present precipitation x (MAGICC value x Standardised GCM pattern of precipitation change, in %)

The following steps were undertaken to produce the Minimum Temperature (July-August), MTminJ-A, scenarios:

1. select 'Scenario Generator' from the main menu
2. select 'Minimum temperature' variable and 'Show change from baseline'
3. select 'July' and 'August' months (coldest winter months) for Temperature minimum.
4. select Year as 1990 for 'Baseline scenario' and for future scenarios select the year 2050.
5. select a GCM and SRES scenario and either Low, Mid or High climate sensitivity. Various GCMs and SRES scenarios were generated to compare the change patterns.

Thirty-nine scenarios were produced in this way, for the South Island of New Zealand only, as MTminJ-A temperature change was expected to be more distinct, given that the south island is at higher latitudes. The number of grid cells per spatial scenario that were above -4^{o}C was counted (see Figure 5.4). This was assuming that cells greater than -4^{o}C indicated broadly, areas which were climatically more suitable and less than -4^{o}C, areas which were climatically unsuitable based on the frost resistance threshold of *Tradescantia*, described in Chapter 2. Figure 5.3 describes the process for selecting the final three scenarios.



Step 1: Create scenarios using all AOGCMs (for MTminJ-A) for the same SRES scenario: A1FI.

Step 2: Select three AOGCMs which give high, medium and low scenarios: HadCM, CSIRO, and CCSR GCMs respectively.

Step 3: For each AOGCM, create climate scenarios using SRES scenarios: A1FI, A1B, A1T, A2, B2, and B1 at Low, Medium and High climate sensitivity: for a total of 39 scenarios.

Step 4: Count the number of cells per spatial scenario > -4°C, the *Tradescantia* frost resistance threshold.

Step 5: Select three climate scenarios that represent a range of Low, Medium and High climate change projections to 2050.

Figure 5.3 Schematic of the steps undertaken to create and select the final climate scenarios, integrated in the species distribution models.

From Figure 5.4 overleaf, the following scenarios were selected based on the -4°C threshold:

1. HadCM A1FI-High: a high scenario (blue bar),
2. CSIRO A1B-Mid: a medium scenario (red bar); and
3. CCSR B1-Low: a low scenario (yellow bar).

At the time of writing this thesis, the AOGCMs that were available were from the IPCC Third Assessment Report (TAR) using climate data from the National Institute for Water and Atmospheric research (NIWA)[42].

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[42] To improve the spatial resolution of the climate scenarios (which were at a 5km scale) for the North Island and South Island, a Fortran programme was used (developed by Dr Yinpeng Li, IGCI). This programme converted the 5km Lat/Long files to interpolated, 100m NZ Map Grid files. These climate change scenarios at 100m were then added to the 100m LENZ TminJ-A raster layer using ArcMap raster calculator. This produced the final climatology layers of the selected future scenarios for the integrated SDM in Chapter 6. The results are shown in Section 5.6. The

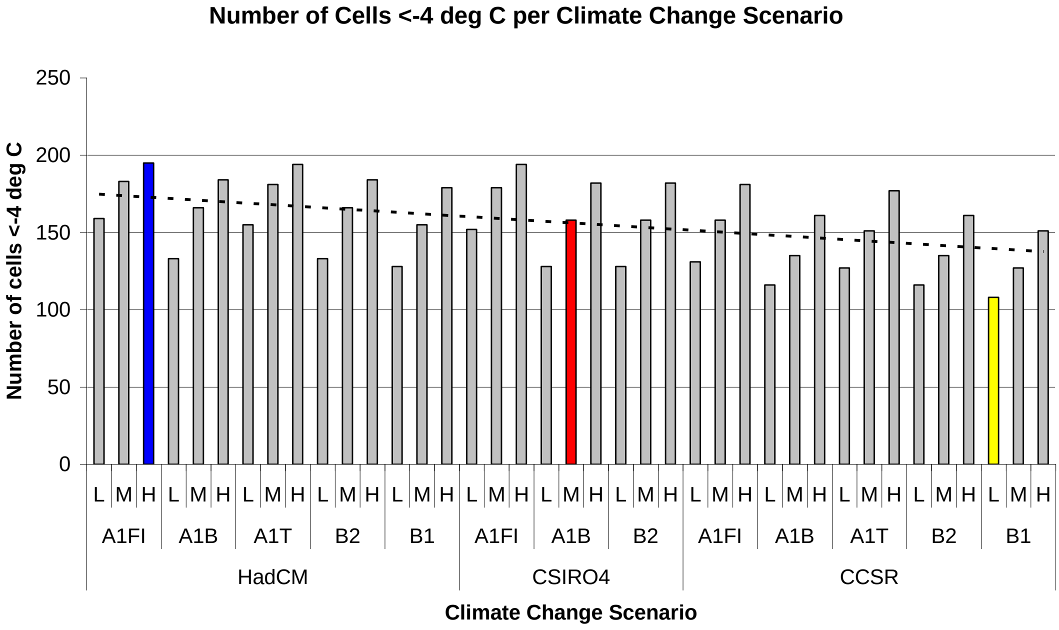

Figure 5.4 Graph showing the HadCM, CSIRO4 and CCSR GCM results, in terms of the number of cells which were <-4oC or the frost resistance threshold for *Tradescantia*. 39 scenarios were generated for comparison, to select three scenarios for sensitivity analysis in the species distribution modelling in Chapter 6.

5.5.6.2 National level: Annual Water Deficit scenarios (AWD)

The same steps were followed to produce the scenarios for Atmospheric Water Balance (except that this was done using the 'Water Resources Impact Model' for Atmospheric Water Balance, AWB). AWB is calculated as:

AWB = Rainfall - Potential Evapotranspiration (PET)

The AW**B** was subsequently converted to an AW**D** layer (the same as the LENZ AWD in Chapter 2) by re-interpolating the scenarios to a 100m New Zealand level map using a LENZ layer mask (to obtain the same boundaries) and then dividing this layer by a constant of 10.

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number of cells in each of the 39 climate scenarios, greater than -4°C, were counted, to indicate the frost resistance threshold spatially for *Tradescantia* (i.e. as being suitable for *Tradescantia*).

5.5.6.3 Bay of Plenty: regional scenarios

The same steps were followed as per section 5.2.5.1, to generate the regional scenarios (Bay of Plenty regional scale) used for the case study area. At this scale, AWB scenarios could not be generated due to lack of solar radiation data. The following scenarios were produced: HadCM-A1FI-High, CSIRO9-A1B-Mid and Darlam-B1-Low.[43] These regional scenarios were then clipped to the scale of the Western Bay of Plenty-Tauranga (at 100m resolution). A grid of regular point was created (one point per 100m), and was then interpolated (using the IDW interpolation technique in ArcMap 9.2) to a new resolution of 15m. This was so that the new climate scenarios could be overlaid with the other habitat and landscape layers at 15m resolution in the landscape-level ENFA analysis in BioMapper, in Chapter 6.

5.6 Results

The six scenarios generated for AWD (November-February), Figures 5.5-5.10, show distinct differences in projected values for the following geographic areas: Bay of Plenty region, Hawkes Bay, North Waikato: around the Coromandel Peninsula, Nelson-Tasman, Marlborough, and the Canterbury Plains. The lowest projected change in AWD occurs under the CCSR B1-Low scenario (ranging approximately between 0-15mm per year), the CSIRO9 A1B-Mid scenario AWD change ranging between 0-44mm per year and the HadCM3 A1FI-High scenario AWD change ranging between 0-100mm) by 2050.

The six scenarios generated for MTminJ-A, Figures 5.11-5.16, show distinct differences in projected change values in particular over the north island of New Zealand. The MTminJ-A change is projected to be the highest for the HadCM A1FI-High 2050 scenario (0.86-1.44^{o}C); with medium change projected under the

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[43] The CCSR GCM was not available at the regional level for the Bay of Plenty, and so the Darlam regional GCM was used as this is a widely used regional GCM for the Australasian region.

CSIRO9 A1B-Mid scenario of (0.54-0.72 ^{o}C) for 2050 and lowest change projected under the CCSR B1-Low scenario for 2050.

At the regional level only MTminJ-A scenarios (for future climate and climate change) were generated (see Figures 5.17-5.22). These showed the highest MTMinJ-A changes are projected under the HadCM A1FI-High scenario (ranging between 1.3-1.4^{o}C); medium changes under the Darlam A1B-Mid scenario (ranging between 0.6-0.7) and the lowest change projected under the CCSR (NIES) B1-Low scenario of 0.3 ^{o}C across the whole region.

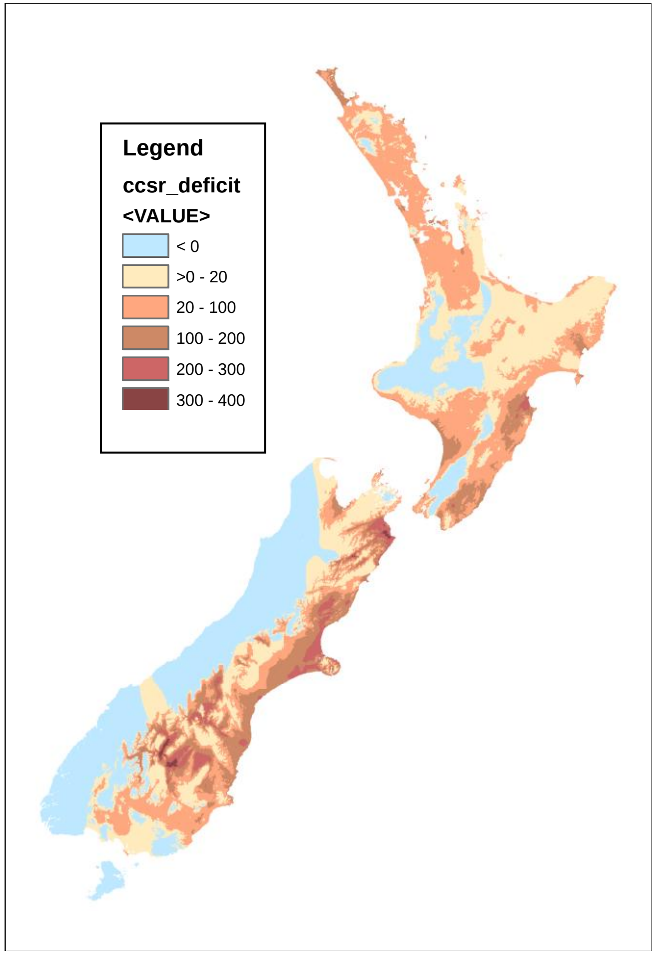


Figure 5.5 Climate scenario for 2050, CCSR:B1-Low: AWD.

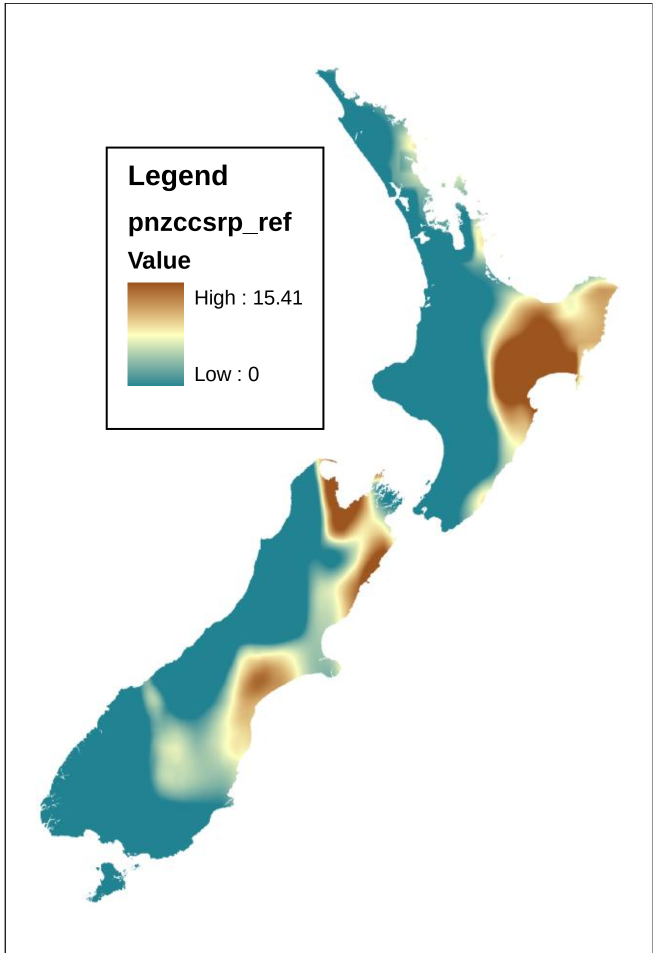


Figure 5.6 Climate change scenario for 2050, CCSR:B1-Low:AWD.

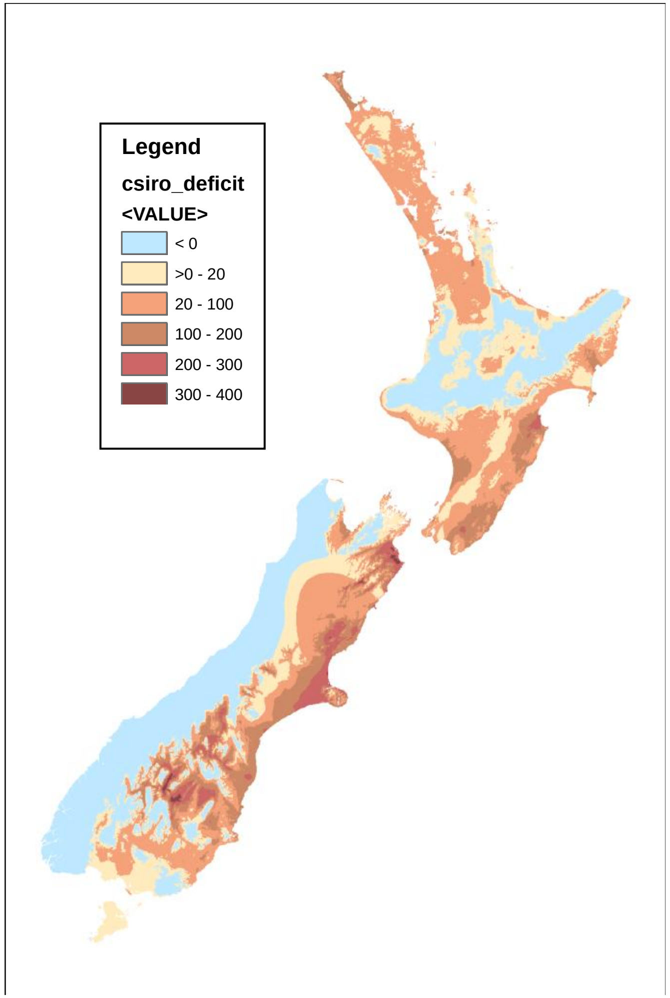


Figure 5.7 Climate scenario 2050, CSIRO9:A1B-Mid: AWD.

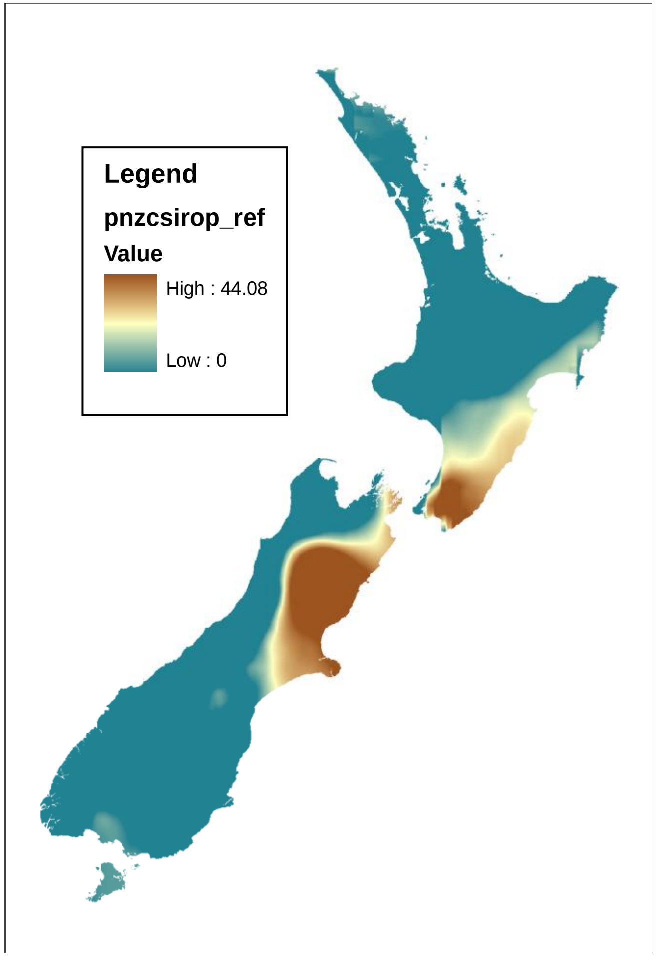
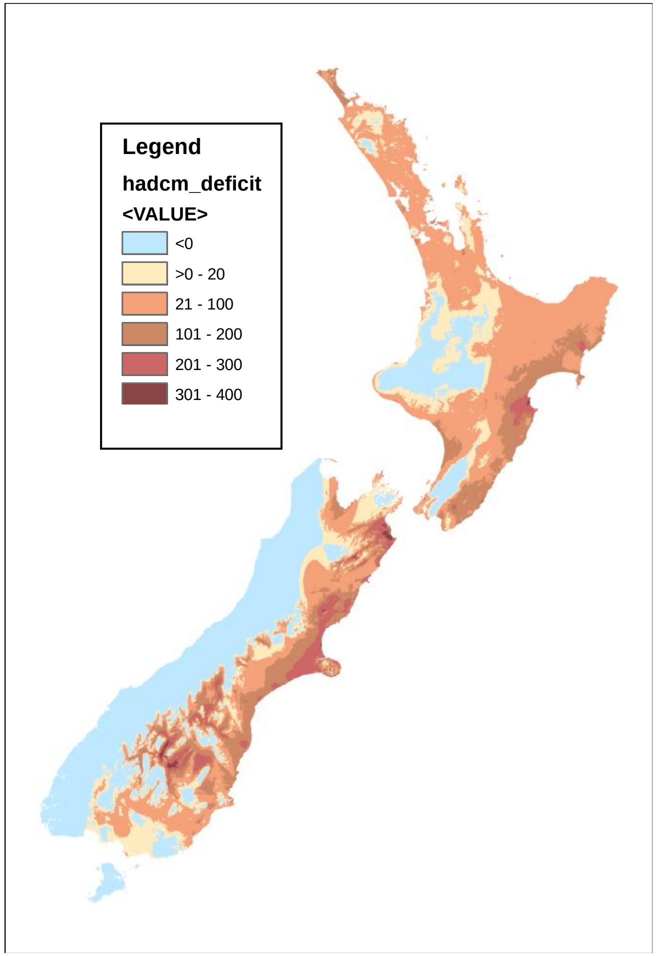


Figure 5.8 Climate change scenario 2050, CSIRO9:A1B-Mid: AWD.



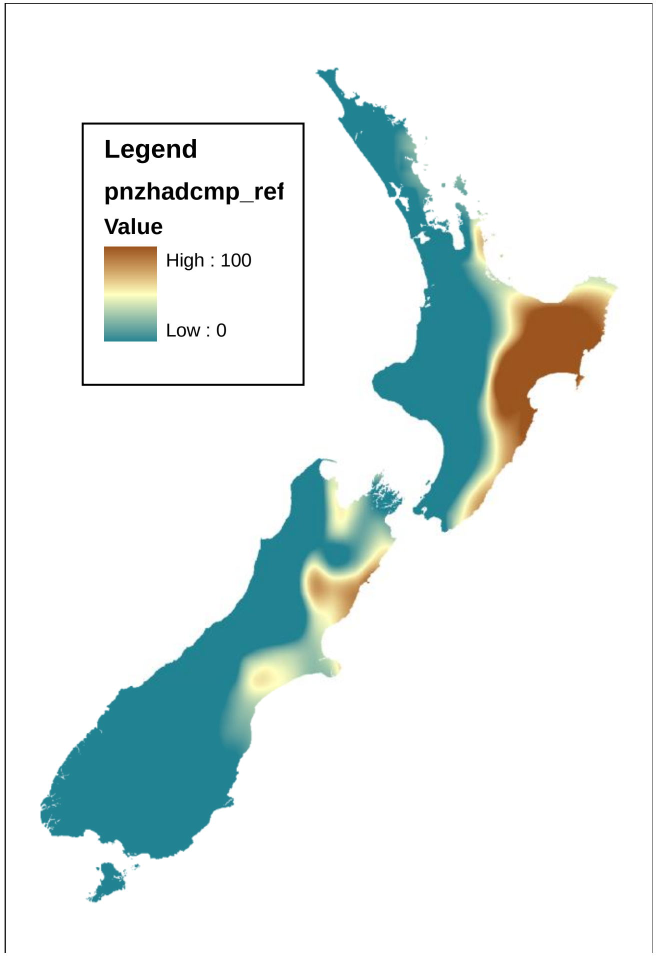
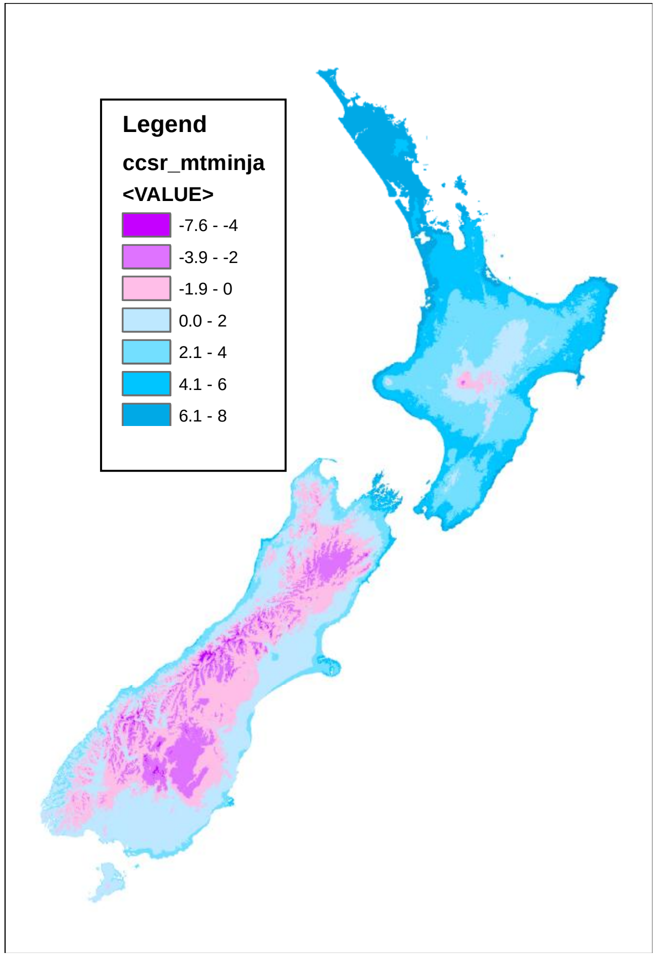


Figure 5.9 Climate scenario 2050, HadCM:A1FI-High: AWD.

Figure 5.10 Climate change scenario 2050, HadCM:A1FI-High: AWD.



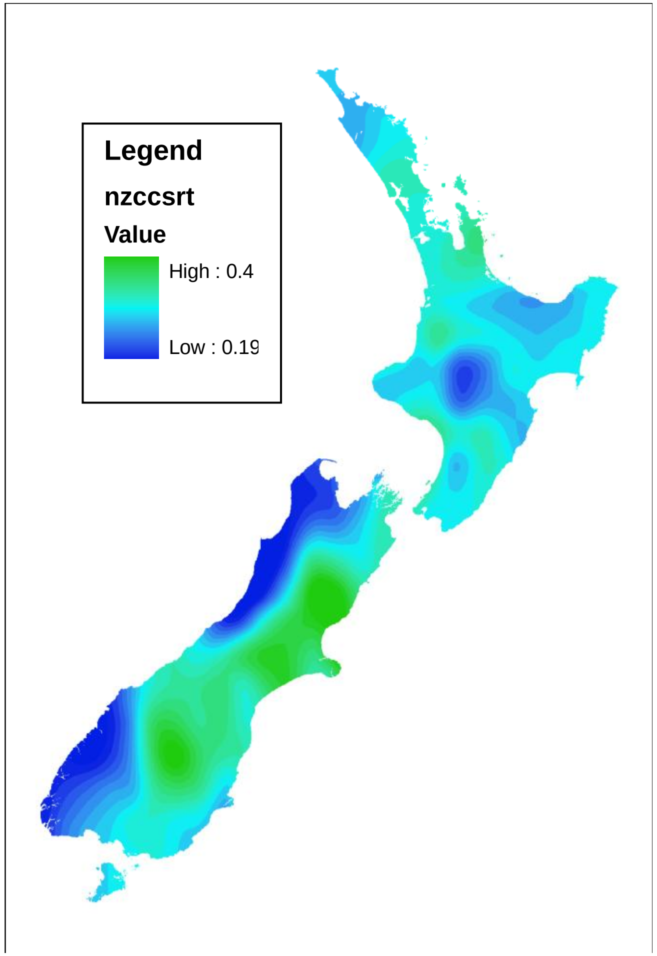


Figure 5.11 Climate scenario 2050, CCSR:B1-Low: MTminJ-A.

Figure 5.12 Climate change scenario 2050, CCSR:B1-Low: MTminJ-A.

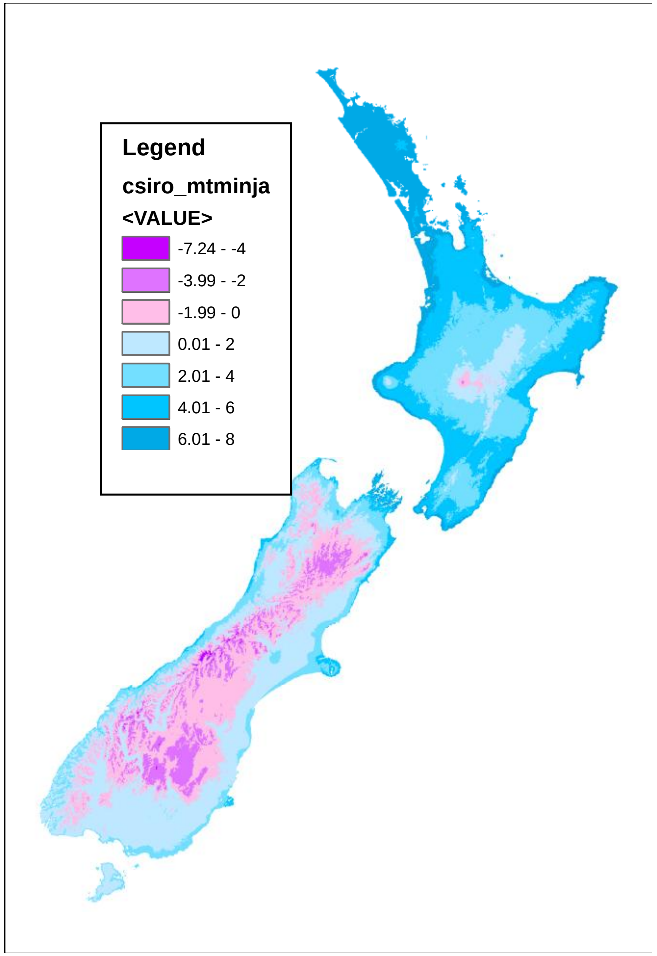


Figure 5.13 Climate scenario 2050, CSIRO9:A1B-Mid: MTminJ-A.

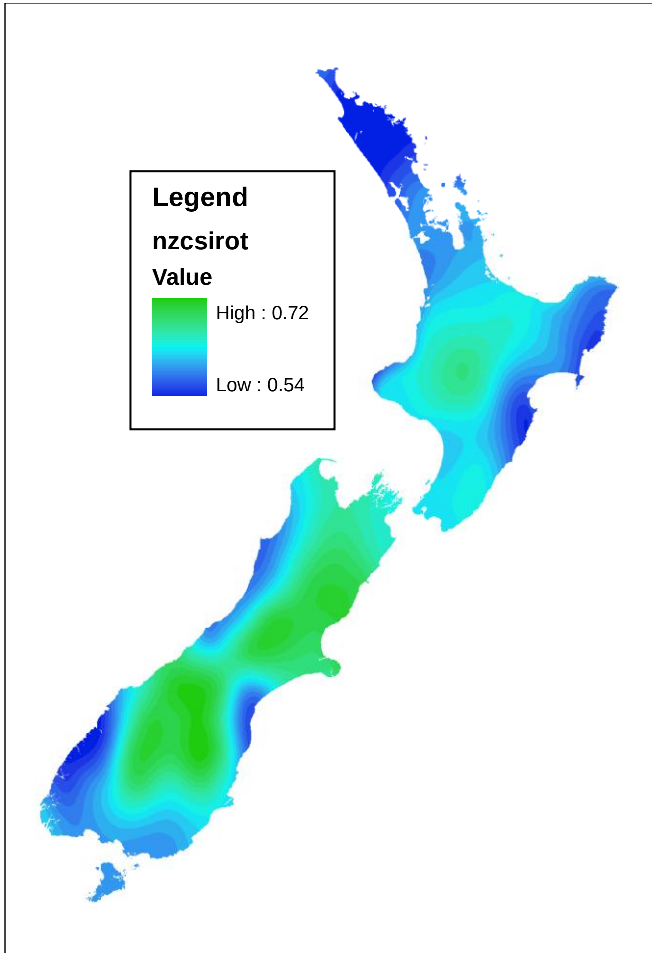


Figure 5.14 Climate scenario 2050, CSIRO9:A1B-Mid: MTminJ-A.

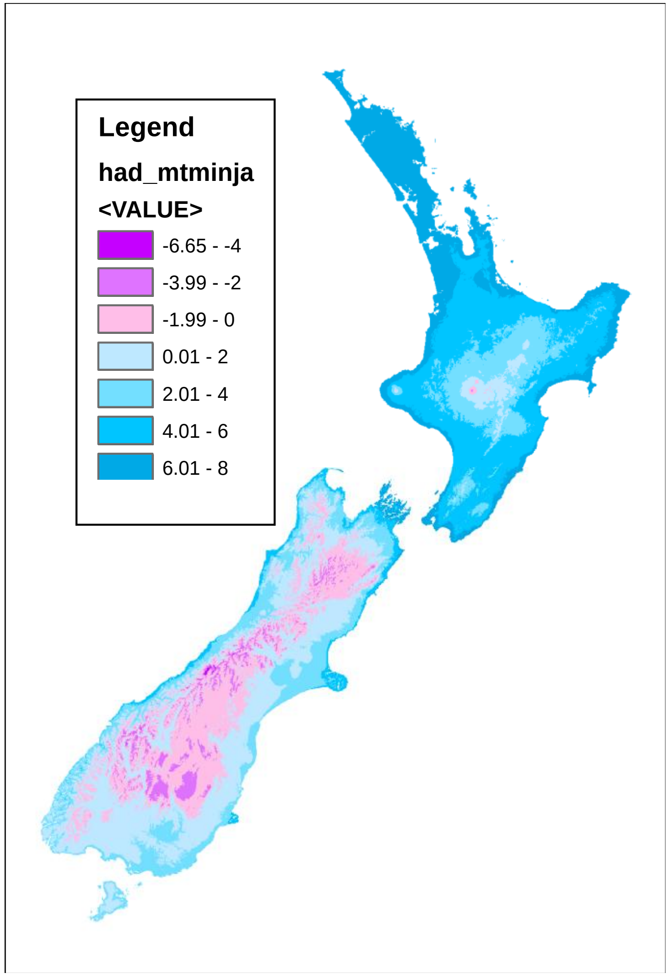


Figure 5.15 Climate scenario 2050, HadCM:A1FI-High: MTminJ-A.

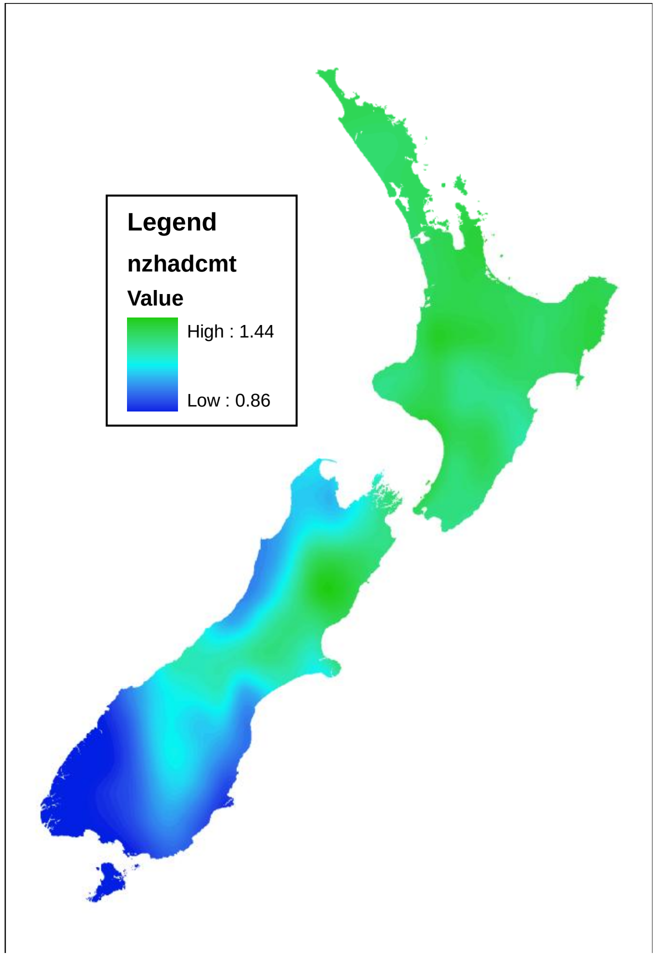


Figure 5.16 Climate change scenario 2050, HadCM:A1FI-High: MTminJ-A.

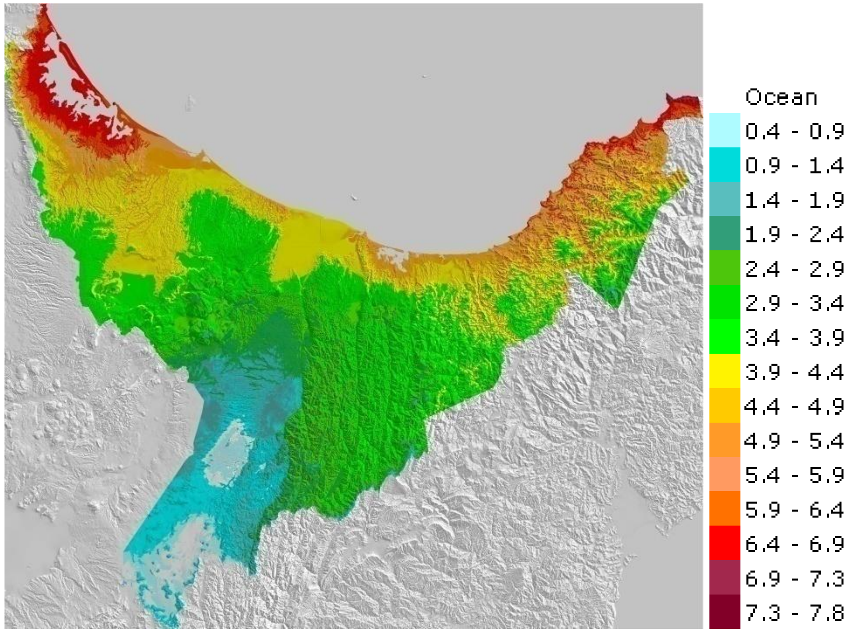


Figure 5.17 Climate scenarios for 2050 for CCSR NIES:B1-Low: MTminJ-A.

Area: Bay of Plenty Region; Model for TMin (°C);Selected Month: 7 8; Scenario generation method: Linked model; Scenario year: 2050; Climate sensitivity: Low; GCM Pattern: CCSR NIES; Emission scenario: IPCC SRES B1.

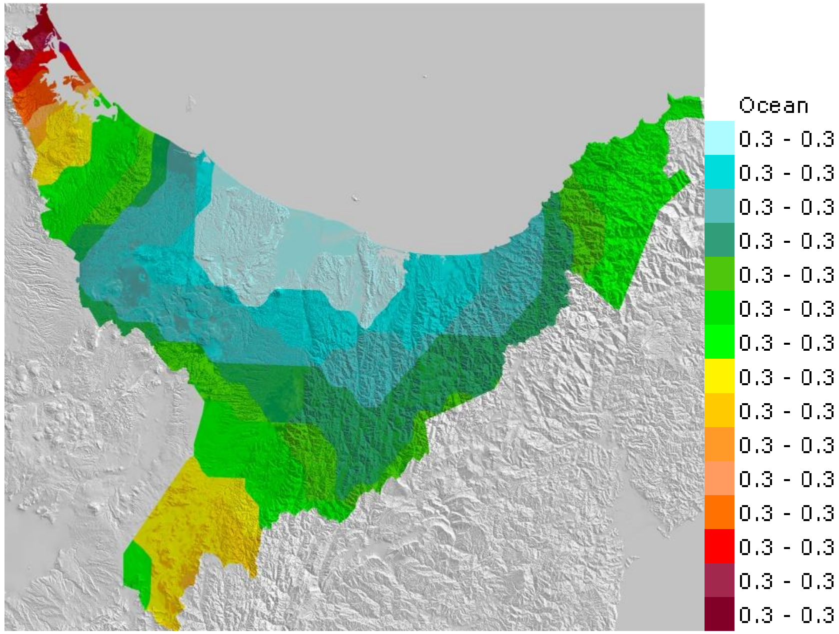


Figure 5.18 Climate change scenario for 2050 for CCSR NIES:B1-Low: MTminJ-A.

Area: Bay of Plenty Region; Model for TMin (°C); Selected Month: 7 8; Scenario generation method: Linked model; Scenario year: 2050; Climate sensitivity: Low; GCM Pattern: CCSR NIES; Emission scenario: IPCC SRES B1.

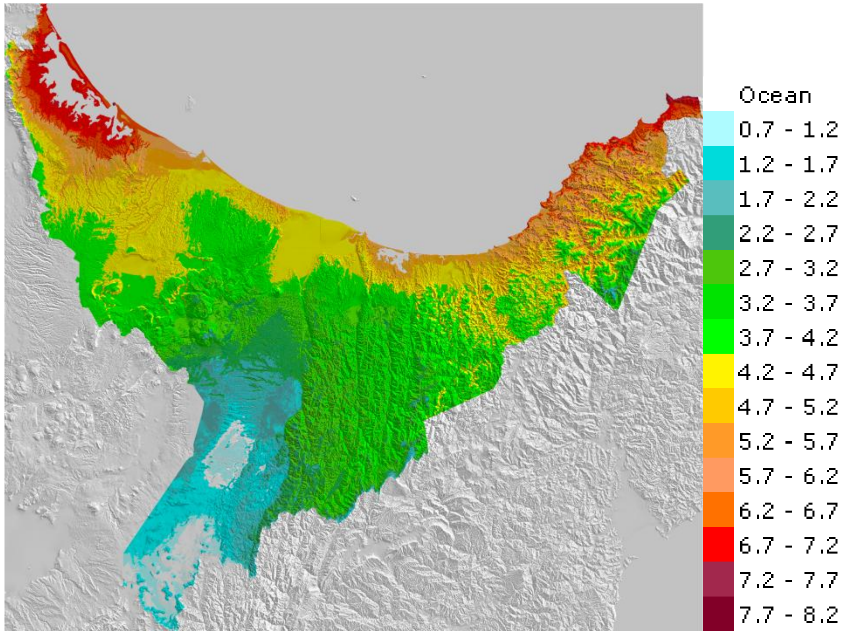


Figure 5.19 Climate scenarios for 2050 for Darlam:A1B-Mid: MTminJ-A.

Area: Bay of Plenty Region; Model for TMin (°C); Selected Month: 7 8; Scenario generation method: Linked model; Scenario year: 2050; Climate sensitivity: Mid; GCM Pattern: Darlam; Emission scenario: IPCC SRES A1B.

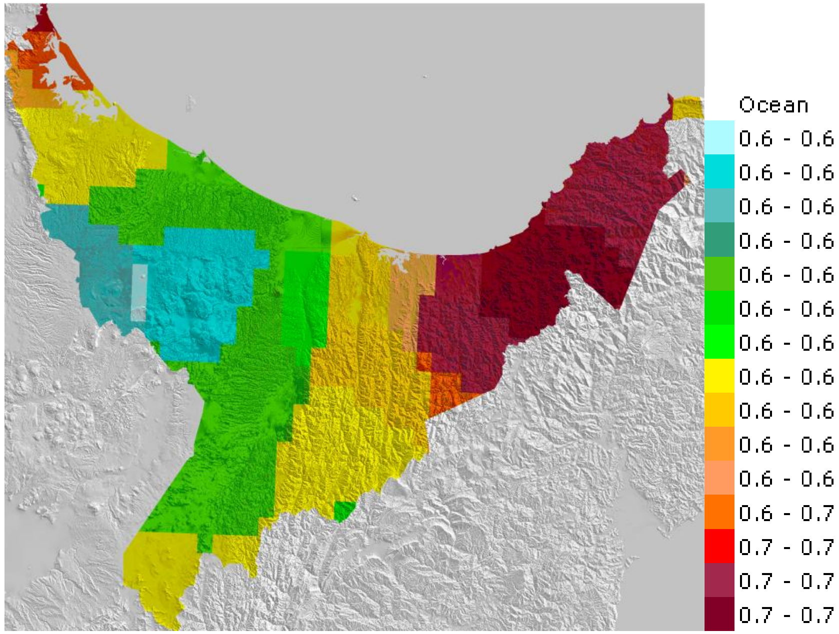


Figure 5.20 Climate change scenario for 2050 for Darlam:A1B-Mid: MTminJ-A.

Area: Bay of Plenty Region; Model for TMin (°C); Selected Month: 7 8; Scenario generation method: Linked model; Scenario year: 2050; Climate sensitivity: Mid; GCM Pattern: Darlam; Emission scenario: IPCC SRES A1B.

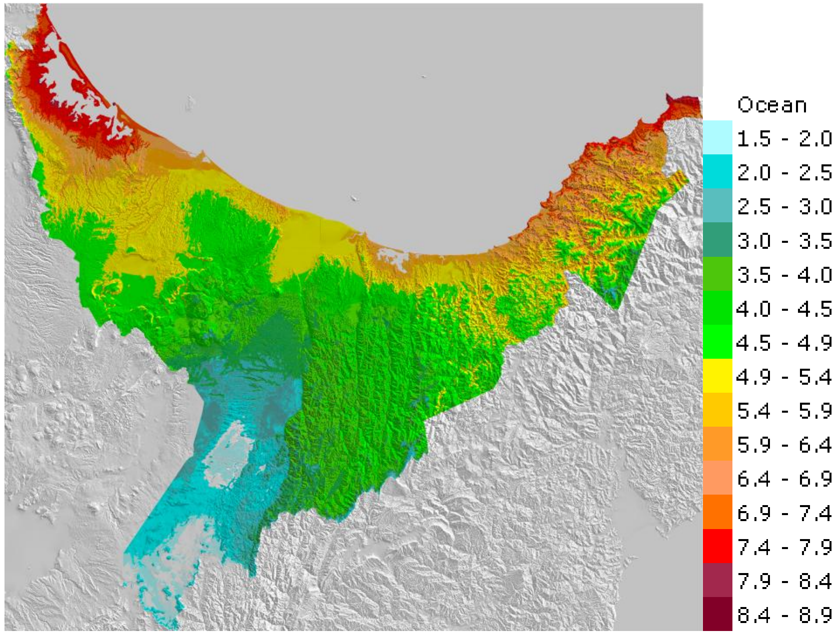


Figure 5.21 Climate scenarios for 2050 for HadCM:A1FI-High: MTminJ-A.

Area: Bay of Plenty Region; Model for TMin (°C); Selected Month: 7 8; Scenario generation method: Linked model; Scenario year: 2050; Climate sensitivity: High; GCM Pattern: HadCM3; Emission scenario: IPCC SRES A1FI.

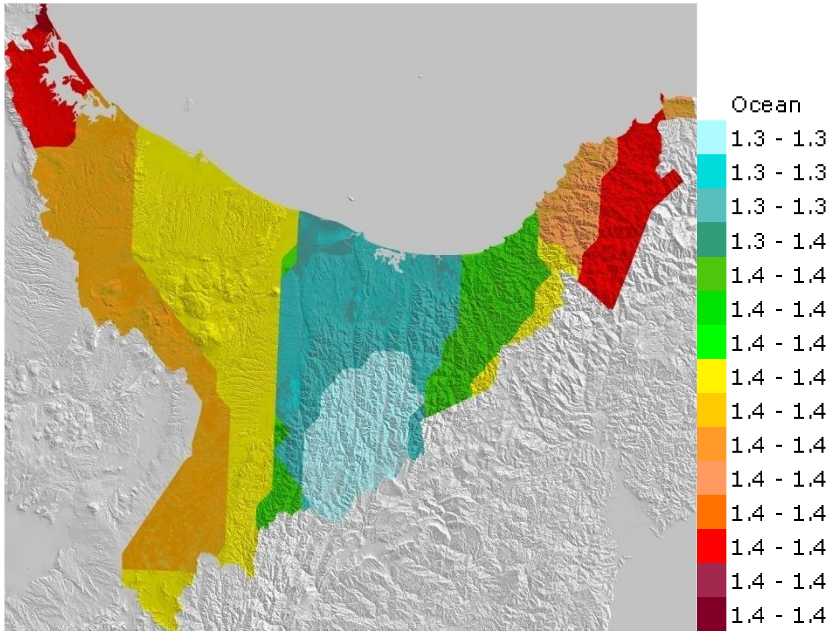


Figure 5.22 Climate change scenario for HadCM:A1FI-High: MTminJ-A.

Area: Bay of Plenty Region; Model for TMin (°C); Selected Month: 7 8; Scenario generation method: Linked model; Scenario year: 2050; Climate sensitivity: High; GCM Pattern: HadCM3; Emission scenario: IPCC SRES A1FI.

5.7 Summary

Methods for generating climate change scenarios were reviewed. For developing spatially explicit scenarios the Atmosphere-Ocean General Circulation Model (AOGCM)s coupled with the SRES Marker scenarios were used at High, Medium and Low sensitivities, to produce three scenarios: CCSR:B1-Low, CSIRO9:A1B-Mid and HadCM:A1FI-High at the national level. At the regional level the scenarios produced were: CCSR NEIS:B1-Low, Darlam:A1B-Mid and HadCM:A1FI-High. The CLIMPACTS Open Framework System was used to generate the scenarios.

The six scenarios generated for AWD (November-February), (three climate scenarios and three climate change scenarios) Figures 5.4-5.9, show distinct differences in projected values for the following geographic areas: Bay of Plenty region, Hawkes Bay, North Waikato: around the Coromandel Peninsula, Nelson-Tasman, Marlborough, and the Canterbury Plains. The AWD is projected to be the highest for the HadCM:A1FI-High 2050 scenario for the Bay of Plenty case study region and lowest for the CSIRO:A1B-Mid 2050 scenario.

The six scenarios generated for MTminJ-A, (three climate and three climate change scenarios) in Figures 5.10-5.15, show distinct differences in projected change values in particular over the North Island of New Zealand. The MTminJ-A change is projected to be the highest for the HadCM:A1FI-High 2050 scenario and lowest for the CSIRO:A1B-Mid 2050 scenario (see Figures 5.16-5.21). This was true both at the national and Bay of Plenty level (where the case study subregion of Western Bay of Plenty and Tauranga is located). In Chapter 6, both the climate scenarios and the land use changes scenarios from Chapters 4 and 5, will be integrated with BioCLIM (climate only) and Biomapper (climate and land use change) to produce the projections of changed species distributions for Tradescantia to assess their combined effects on this species' future distribution.

6 Chapter 6: Integrated species distribution modelling

6.1 Introduction

Integrated assessment is an interdisciplinary process which, in the context of biodiversity and natural systems, relates to the vulnerability of and impact on natural systems by climate and land use changes (and other socio-ecological effects such as pollution) at multiple spatio-temporal scales. The ‘vulnerability’ component of the integrated assessment in the context of invasive species like *Tradescantia* is considered equivalent to the ‘invasibility’ of ecosystems or habitats and climate and land use changes affect this invasibility at multiple scales. This chapter, therefore, integrates the species modelling approaches from Chapter 3 with the land use change scenarios and climate change scenarios from Chapters 4 and 5 respectively. This produces the species distributions for *Tradescantia* under various *combinations* of climate and land use change at the national and landscape-levels, using the ‘Extrapolation Module’ of Biomapper. The extrapolated future integrated scenarios produce Habitat Suitability Maps which show the change in the realised species distribution of *Tradescantia* in New Zealand under the various scenarios.

The integrated assessment methodology began by integrating existing information relating to invasibility at the national and landscape levels. Following the UNDP (2004) guidelines for integrated assessment, the first step was to synthesise and reduce all relevant information, thresholds and other factors to the most important information as inputs into producing the baseline realised species distribution (in Chapter 3). This baseline was then used to describe the current situation and provide the species distribution for *Tradescantia* against which future changes in invasibility are assessed in this Chapter. The purpose of this activity was to identify and characterize the way in which the selected landscape is *sensitive* to climate change and/or land use change, and can thus provide information on the potential future vulnerabilities/invasibility (via the Habitat Suitability Maps generated by the species distribution models).

6.2 Construction of potential future species distribution for T.fluminensis

6.2.1 Model generation

The baseline models developed in Chapter 3 formed the basis for extrapolating to produce the future integrated scenarios. To create an extrapolation model, all the same steps involved in building a standard habitat suitability (HS) model were performed. The various combinations of models produced in Chapter 3 were used to generate extrapolation models that could be used with the corresponding future values of those variables. It was found that at the 15m x 15m landscape resolution, inclusion of three or more variables and three or more extracted factors required more computer RAM than even a 2GB computer could provide. Therefore, to produce the future integrated scenarios, the 50m x 50m resolution was used. Once a satisfactory HS model was produced as in Chapter 3, it was ready to be extrapolated using the Biomapper ‘Extrapolation Module’ and the ‘Generate Model’ option.

The Extreme Optimum Median algorithm was selected, because of its ability to model distributions where the species’ optimum lies at the edge of its fundamental or realised niche (Braunisch et al., 2008). This was the case for *Tradescantia*, particularly at the landscape scale. At the national level, the scenarios produced for (1) MTMinJ-A and (2) AWD for the scenarios CCSR:B1-Low, Darlam:A1B-Mid and HadCM:A1FI-High in Chapter 5 were used at a spatial resolution of 500m x 500m, as this algorithm could not produce extrapolations at the original resolution of 100m x 100m. For the landscape level analyses the scenarios for (1) MTMinJ-A (2) Proximity to Urban and (3) Proximity to Streams were used at a 50m x 50m resolution. The three variables per combined scenario (CC+LUC) produced three factors each (refer to Table 6.1 for the EGVs used). All three factors were used[44].

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[44] The number of factors needs to be selected carefully. More than four factor maps put a heavy strain on computation time and hard disk space. Therefore, Biomapper documentation

Combined Scenario	**CC/LUC**	**Variables (EGVs)**	**EGV Description**
National level			
1. CCSR:B1-Low	CC	MTminJ-A and AWD	Both EGVs perturbed using the CCSR GCM
2. CSIRO9: A1B-Mid	CC	MTminJ-A and AWD	Both EGVs perturbed using the CSIRO9 GCM
3. HadCM: A1FI-High	CC	MTminJ-A and AWD	Both EGVs perturbed using the HadCM GCM
Landscape level			
1. CCSR-SmartGrowth	CC	MTminJ-A (CCSR: B1-Low)	Baseline MTminJ-A perturbed using the CCSR GCM in CLIMPACTS
	LUC	Proximity to SmartGrowth	Euclidean distance to new SmartGrowth Urban areas for 2050, using ArcGIS.
	LUC	Proximity to Streams[45]	Euclidean distance to streams using ArcGIS.
2. Darlam-SmartGrowth	CC	MTminJ-A (Darlam:A1B-Mid)	Baseline MTminJ-A perturbed using the Darlam GCM in CLIMPACTS
	LUC	Proximity to SmartGrowth	Ibid.
	LUC	Proximity to Streams	Ibid.
1. HadCM-Buildout	CC	MTminJ-A (HadCM:A1FI-High)	Baseline MTminJ-A perturbed using the HadCM GCM in CLIMPACTS
	LUC	Proximity to Buildout	Euclidean distance to new ‘Buildout’ urban areas for 2050, using ArcGIS.
	LUC	Proximity to Streams	Ibid.

Table 6.1Description of the scenario variables used to construct the combined scenarios, run the extrapolations and produce the three future scenarios.

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recommends that there be a careful trade-off between the number of factors chosen and the resolution of the resulting Habitat Suitability Maps (Hirzel 2008).

[45] The ‘Proximity to streams’ variable is the same under each scenarios, as it is assumed that the stream network will not undergo significant spatial changes, although natural change and human-induced changes through channelisation etc, may cause localized changes.

An extrapolation table was produced which provided the basic information about the original EGVs used to produce the baseline HS model in Chapter 3. The original EGVs refer to EGVs prior to being transformed (e.g. by the Box-Cox algorithm). This table listed all EGVs, which transformation was used (or Identity if no transformation was used) and what was the original value range of the variable. This range was important because it allowed comparison of the original baseline with the one to which the model was applied in each future scenario and then allowed the extrapolation margin to be estimated. The factor resolution, i.e. the number of classes into which each factor will be decomposed, was selected as 50. High values mean smoother HS maps (but probably misleadingly smoother), larger look-up and count tables and longer processing time.

The future scenarios required an extrapolation margin, in % of the original range. An extrapolation margin means that HS values are stored for factor value combinations ranging some percentage below and above the original range. This was required because MTminJ-A scenarios (at the national and landscape levels) and AWD (at the national level), had higher maximum values, resulting in a few MTminJ-A or AWD values being outside the upper end of the original value range. This ‘Generate Model’ procedure produced an extrapolation Lookup Table a Counts Table which contained all the extrapolation information and this will be referred to later.

6.2.2 Model application

The above extrapolation model was applied to the new scenario layers by using the ‘Apply Model’ option of the ‘Extrapolation Module’. This required checking that each original baseline EGV matched with its corresponding scenario EGV. Minimum and maximum values of the original EGVs were compared to those of the original EGVs to see where an extrapolation margin was needed.

It was necessary to select what would be included in the HS map for the following options:

1. Extrapolated cells: cells where factor combination values fell out of the original factor range but were inside the margins set for extrapolation when building the baseline distribution model.
2. Interpolated cells: cells where the factors value combination did not exist in the baseline distribution model, but still fell within the original range.
3. Direct cells: cells that had at least some occurrences in the original area.

The procedure also produced a spatial 'Count Map' with the following values (Hirzel, 2008):

1. >0: **Direct cells -** i.e., with the value indicating how many cells in the extrapolated map had a similar factor value combination in the original area (the higher this number, the more reliable the HS value);
2. 0: **Interpolated cells** – where cells have factor value combinations which do not exist in the original area, however still fell within the original range;
3. -10: **Extrapolated cells** – where cells have factor value combinations which fall outside of the original factor range but inside the margins set for extrapolation when building the model; and
4. -20: **Not-computed cells** – where cells were out of the extrapolation margins and could not be given a HS value.

The reliability of the output scenario Habitat Suitability map decreases from 1-4 above. The count map was useful in identifying if there were any 'not computed' cells. The aim was to produce a map which had the highest number of cells >0 using the direct cell factor values from the baseline model. Extrapolated cells were inevitable, particularly because of the climatic EGVs (MTminJ-A and AWD), as the range of values changed per EGV when they were perturbed for climate change.

Table 6.2 shows the extrapolation margin that was estimated for each of the combined scenarios at the national and landscape level in this study. These extrapolation margins are specific to the EGVs used and to the landscape selected and will need to be adjusted as required when different EGVs or landscapes are tested.

Combined Scenario	**Extrapolation margin (%)**
National level	
1. CCSR:B1-Low	1
2. CSIRO9: A1B-Mid	1
3. HadCM: A1FI-High	4
Landscape level	
1. CCSR:B1-Low-SmartGrowth	5
2. Darlam:A1B-High-SmartGrowth	16
1. HadCM:A1FI-High-Buildout	35

Table 6.2 Combined scenarios and the percentage extrapolation applied. The landscape level extrapolations required higher extrapolation margins than at the national level in producing the extrapolated species distributions.

6.3 Results: national level species distribution of T.fluminensis

The national-level distribution of *Tradescantia*, under all three of the CCSR:B1-Low, CSIRO9:A1B-Mid and HadCM:A1FI-High combined scenarios, shows an increase in Habitat Suitability for *Tradescantia*, primarily on the North Island (Figures 6.1-6.6). In the South Island, under all three combined scenarios, the main areas to increase in suitability are along the coastal margin of the West Coast, around Nelson and Tasman, and along the coastal margin between Picton and Christchurch on the Kaikoura Coast. Apart from these areas, the rest of the South Island remains largely climatically unsuitable, i.e. HS<10.

The combined CCSR:B1-Low and CSIRO9:A1B-Mid scenarios show that on the North Island maximum habitat suitability is likely to shift southward. The Eastern Bay of Plenty, Gisborne, Hawkes Bay, Wairarapa, Manawatu and lowland parts of the Wellington region are all likely to become increasingly climatically suitable. Large parts in the north of the North Island become largely climatically marginal for *Tradescantia*, while Auckland and Waikato remain the largest geographic area of climatically suitable habitat in the country, extending all the way inland from both east and west coasts. The central North Island, around the Central Plateau, remains in large part either marginally suitable or unsuitable, as under the Baseline scenario. This marginal suitability extends from the Central Plateau to Mt. Egmont on the West Coast and through the Uruwera Ranges on the East Coast of the North Island. On the South Island, the climatic suitability does not change discernibly under the CCSR:B1-Low scenario. The only area which becomes substantially more suitable is the coastal edge between Marlborough and Christchurch and Banks Peninsula, along the Kaikoura Coast. The HadCM:A1FI-High combined scenario shows a larger shift in climatically suitable habitat, particularly for the North Island. Under this scenario, most of the Uruwera Ranges which were only marginally suitable under the Baseline, CCSR:B1-Low and CSIRO9:A1B-Mid scenarios become highly suitable. Other inland parts of the North Island also increase in climatic suitability, inland towards the Central Plateau. Interestingly, Auckland becomes more marginal climatically. On the South Island the coastal edge from the northwest tip through Takaka, Nelson, the Marlborough Sounds and south along the eastern coastal edge into Christchurch and the Banks Peninsula becomes discernibly more climatically suitable under the HadCM:A1FI-High combined scenario.

Figures 6.2, 6.4 and 6.6 reclassify the HS Map outputs from the CCSR:B1-Low, CSIRO9:A1B-Mid and HadCM:A1FI-High combined scenarios into ‘Core’, ‘Marginal’ and ‘Unsuitable’ areas using the following Habitat Suitability Values as thresholds, as used in Chapter 3. On this basis, Tables 6.3 and 6.4 show the changes in the Core, Marginal and Unsuitable areas for the North and South Islands independently under each of the three combined scenarios. Figure 6.7 shows the percentage changes in area for each of the combined scenarios measured against the baseline, while Figure 6.8 and 6.9 depict these changes by calculating the changes per region (using regional council boundaries for New Zealand) and per Department of Conservation regional administrative areas (using the DoC Conservancy boundaries). This figure shows that the core areas increase across all regions and DoC conservancies, with no decreases recorded. Marginal areas typically decrease, except for the West Coast and Southland where minor increases (<1%) are recorded.

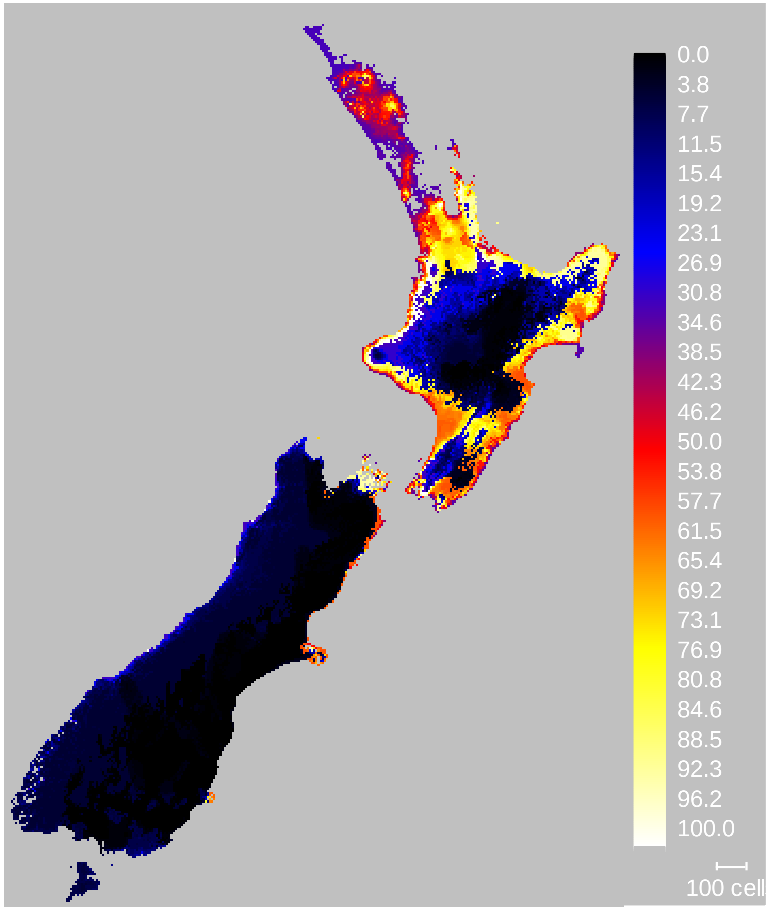


Figure 6.1 CCSR:B1-Low combined scenario for 2050 of the potential distribution of *Tradescantia*.

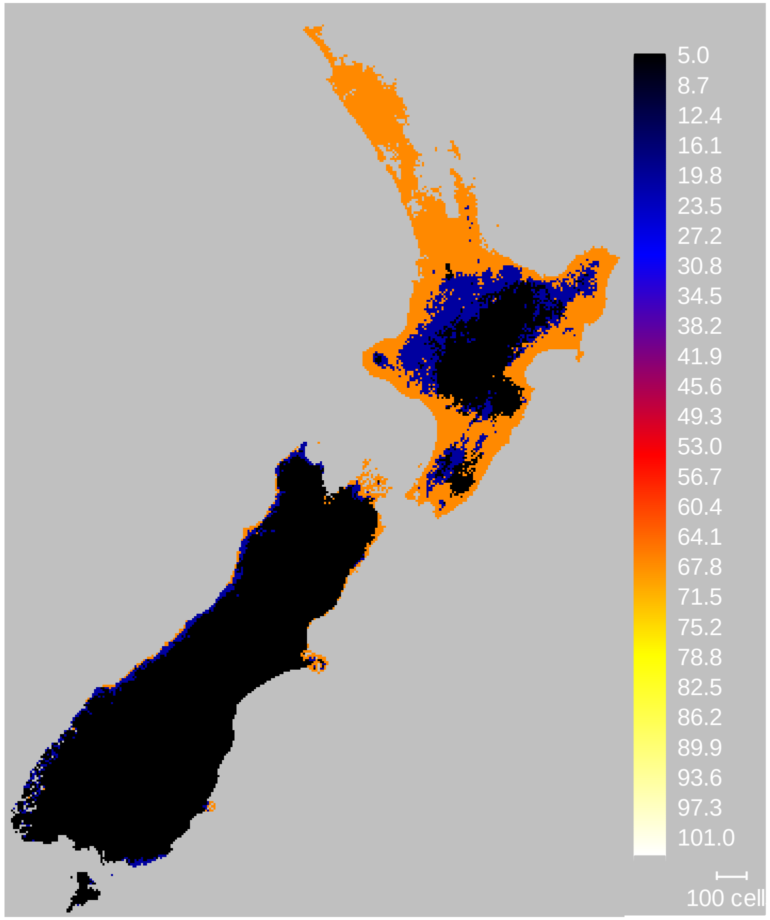


Figure 6.2 CCSR:B1-Low combined scenario for 2050: core, marginal and unsuitable areas for *Tradescantia*.

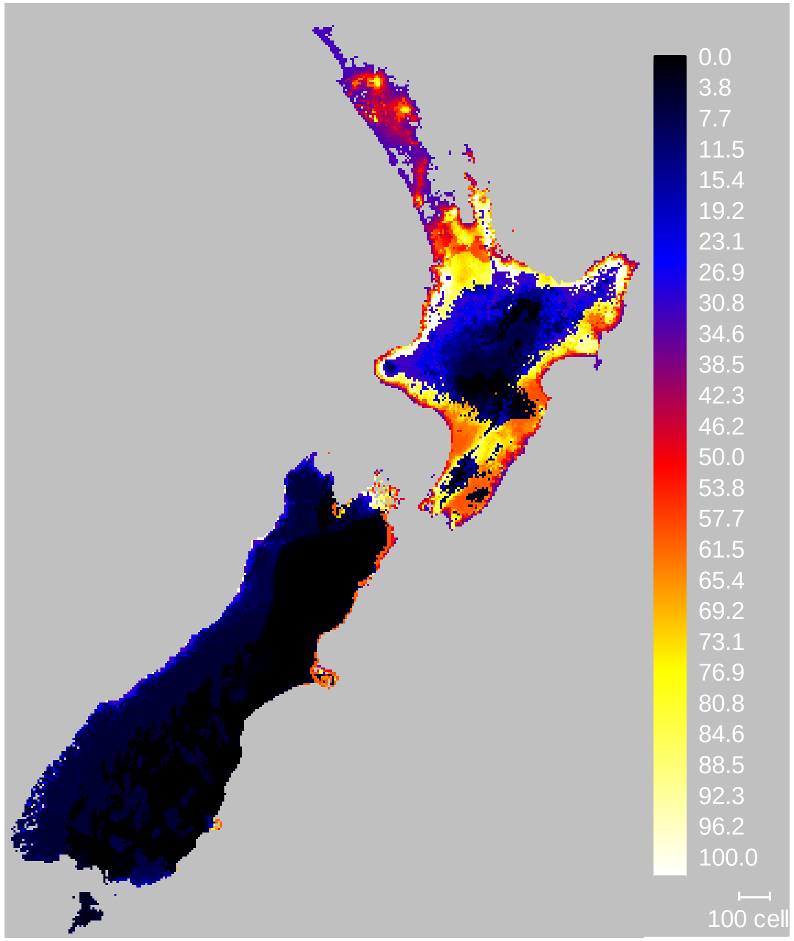


Figure 6.3 CIRO9:A1B-Mid combined scenario for 2050 of the potential distribution of *Tradescantia*.

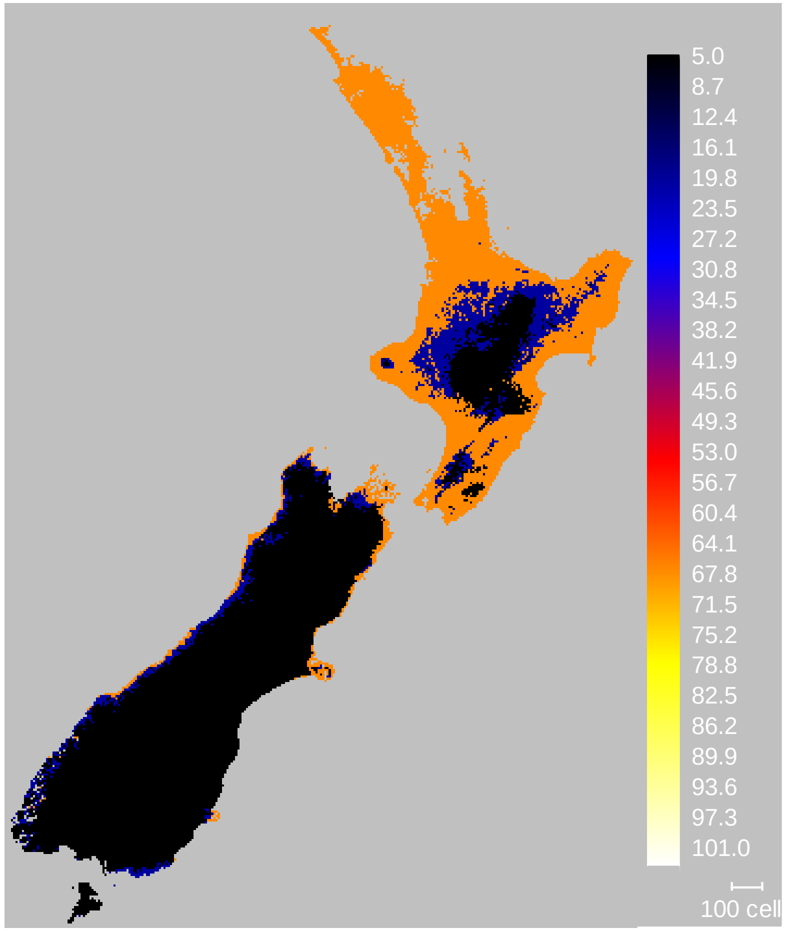


Figure 6.4 CSIRO9:A1B-Mid combined scenario for 2050: core, marginal and unsuitable areas.

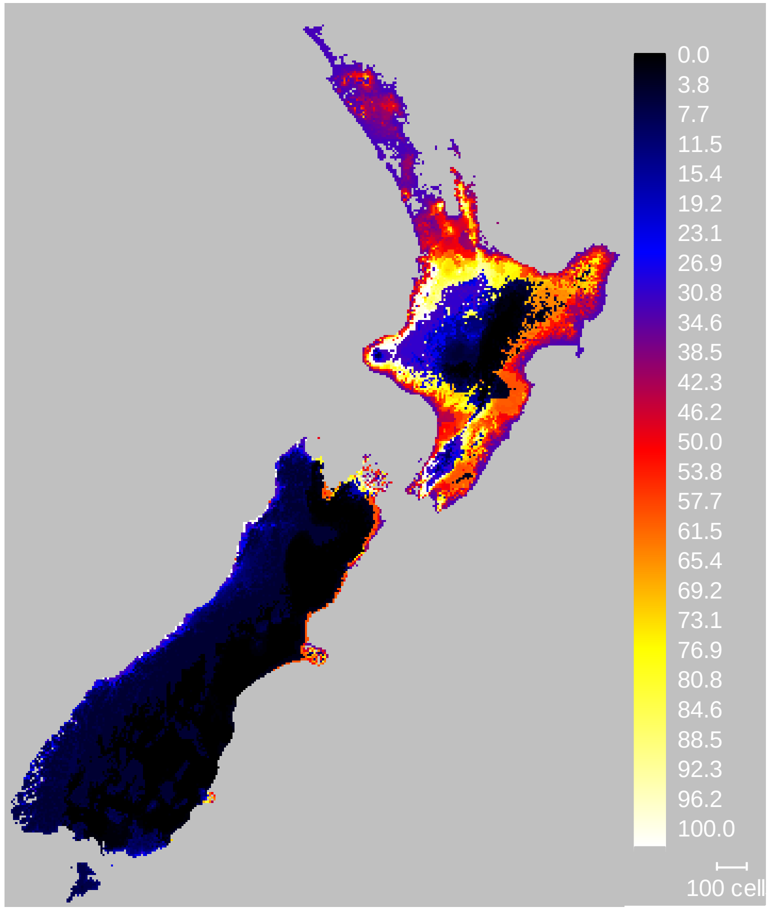


Figure 6.5 HadCM:A1FI-High combined scenario for 2050 of the potential distribution of *Tradescantia*.

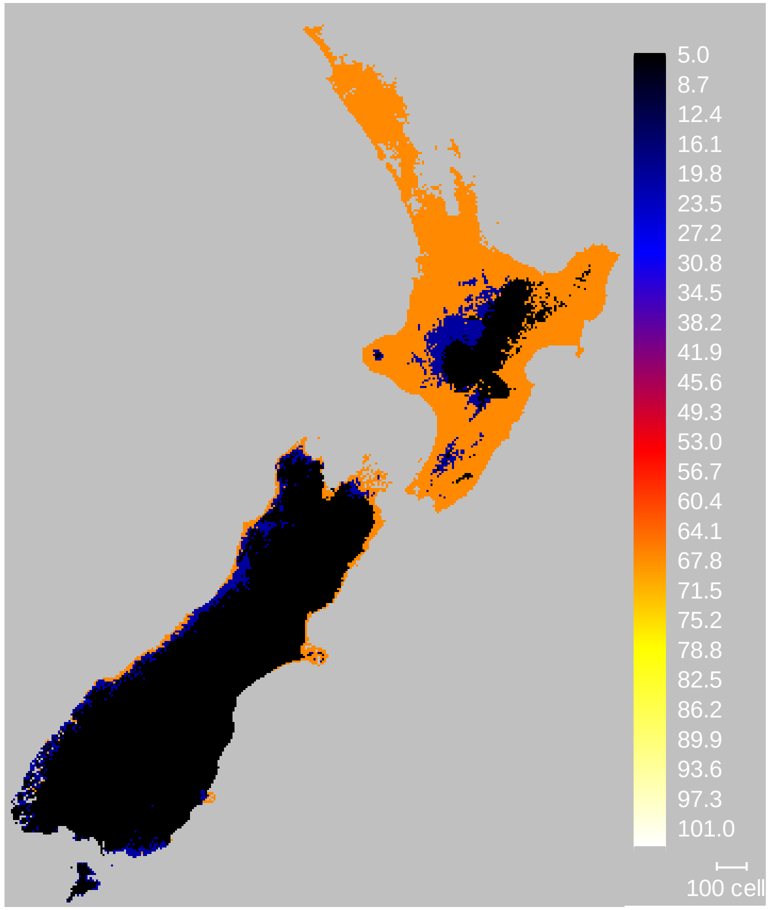


Figure 6.6 HadCM:A1FI-High combined scenario for 2050: core, marginal and unsuitable areas for *Tradescantia*.

Climate scenario	**Core Areas (m^2)** **(% of Total Area)**		**Marginal Areas (m^2)** **(% of Total Area)**		**Unsuitable Areas (m^2)** **(% of Total Area)**	
	NI	**SI**	**NI**	**SI**	**NI**	**SI**
Baseline MTminJ-A + Deficit	118713 **(11)**	2995 **(0.3)***	226497 **(21)**	33122 **(3)**	110910 **(10)**	573869 **(54)**
CCSR MTminJ-A + Deficit	259721 **(24)**	18149 **(2)**	85489 **(8)**	26744 **(3)**	109831 **(10)**	564553 **(53)**
CSIRO9 MTminJ-A + Deficit	255278 **(24)**	27174 **(3)**	305220 **(29)**	33701 **(3)**	76360 **(7)**	548571 **(51)**
HadCM MTminJ-A + Deficit	351796 **(33)**	34024 **(3)**	35012 **(3)**	41546 **(4)**	68233 **(6)**	533876 **(50)**

Table 6.3 The Areas (m^2) and as a percentage of the total area of New Zealand for core, marginal and unsuitable areas for each of the combined scenarios.

Climate scenario	**Δ Core Areas** **(% of Total Area)**		**Δ Marginal Areas** **(% of Total Area)**		**Δ Unsuitable Areas** **(% of Total Area)**	
	NI	**SI**	**NI**	**SI**	**NI**	**SI**
CCSR MTminJ-A + Deficit	+13.2	+1.4	-13.2	-0.6	-0.1	-0.9
CSIRO9 MTminJ-A + Deficit	+12.8	+2.3	+7.4	+0.1	-3.2	-2.4
HadCM MTminJ-A + Deficit	+21.8	+2.9	-17.9	+0.8	-4.0	-3.7

Table 6.4 The change to core, marginal and unsuitable areas on the North and South Islands, as a percentage of the total area of New Zealand for each of the combined scenarios.

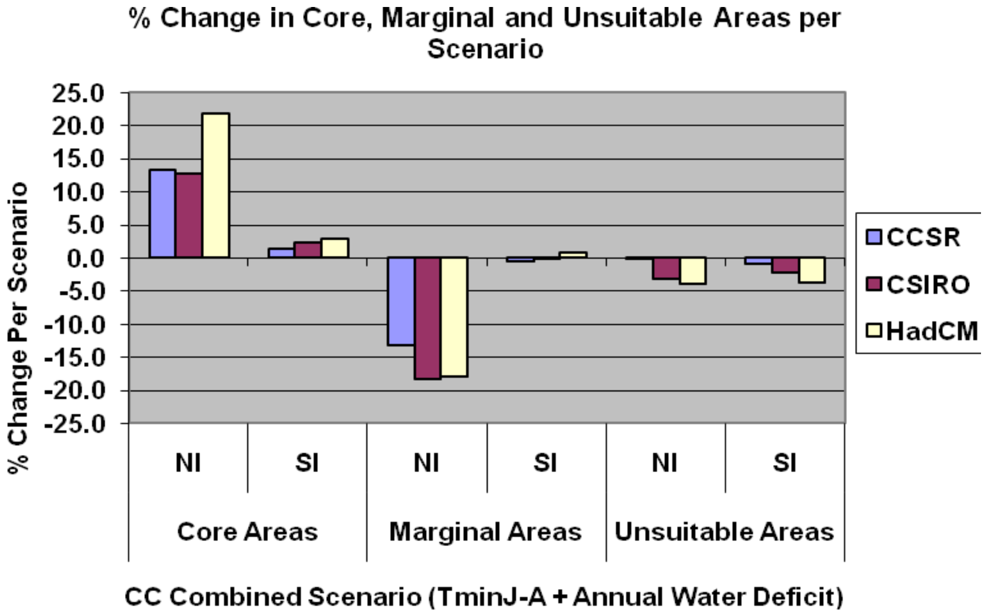


Figure 6.7 Percentage change in core, marginal and unsuitable areas per combined scenario.

Administrative Areas	**Core Areas (m^2): Cell Counts per Future Scenario (2050) (% of Total Area)**			
	Baseline	CCSR:B1-Low	CSIRO9:A1B-Mid	HadCM:A1FI-High
DoC Conservancies	121708	277870	112233	674384
Regions	120919	261163	680696	277688

Table 6.5 The number of raster cells combined for all core areas within national administrative areas: Department of Conservation Conservancies and Regional Council Boundaries.

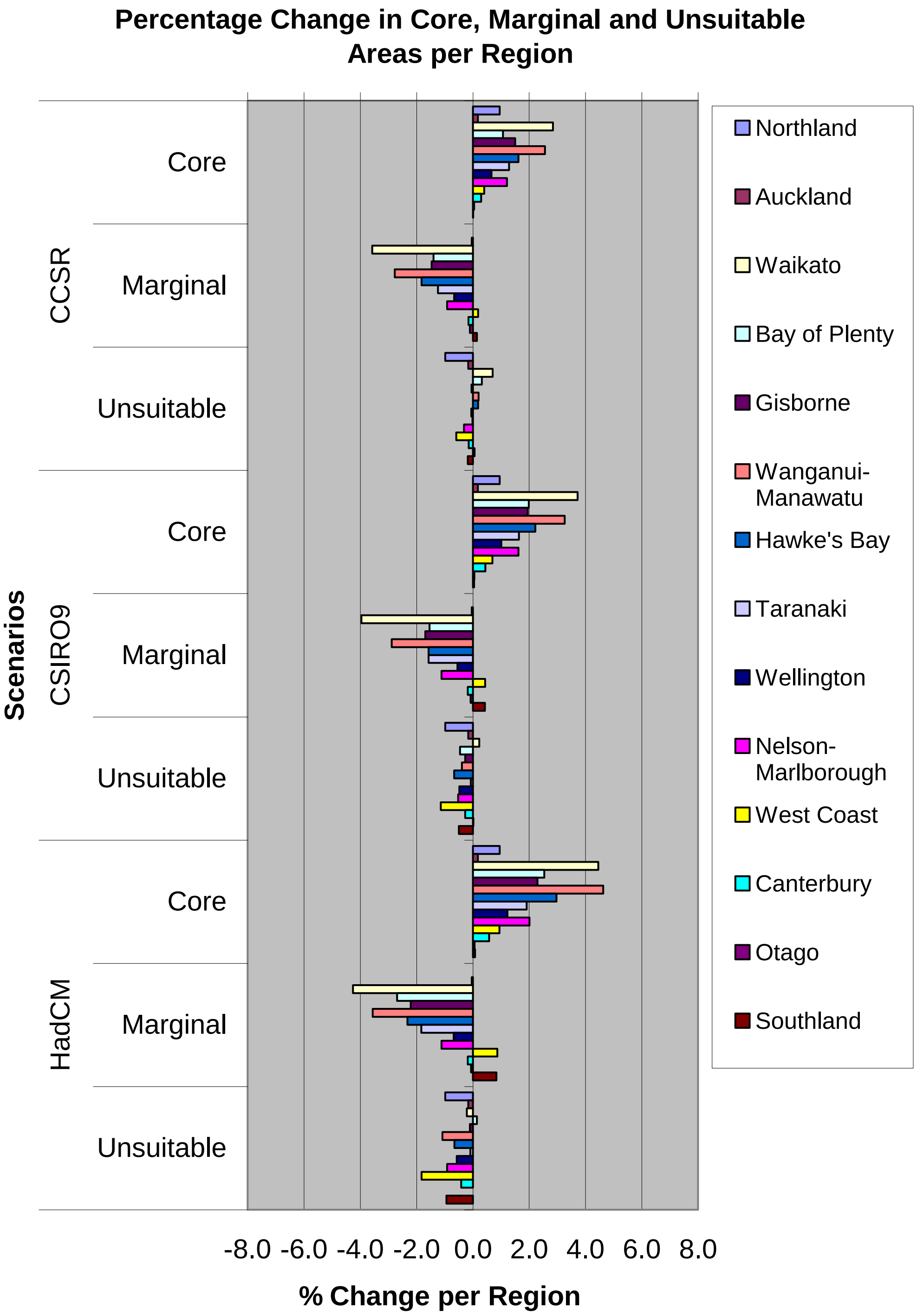


Figure 6.8 Percentage change in core, marginal and unsuitable areas per combined scenario and per region.

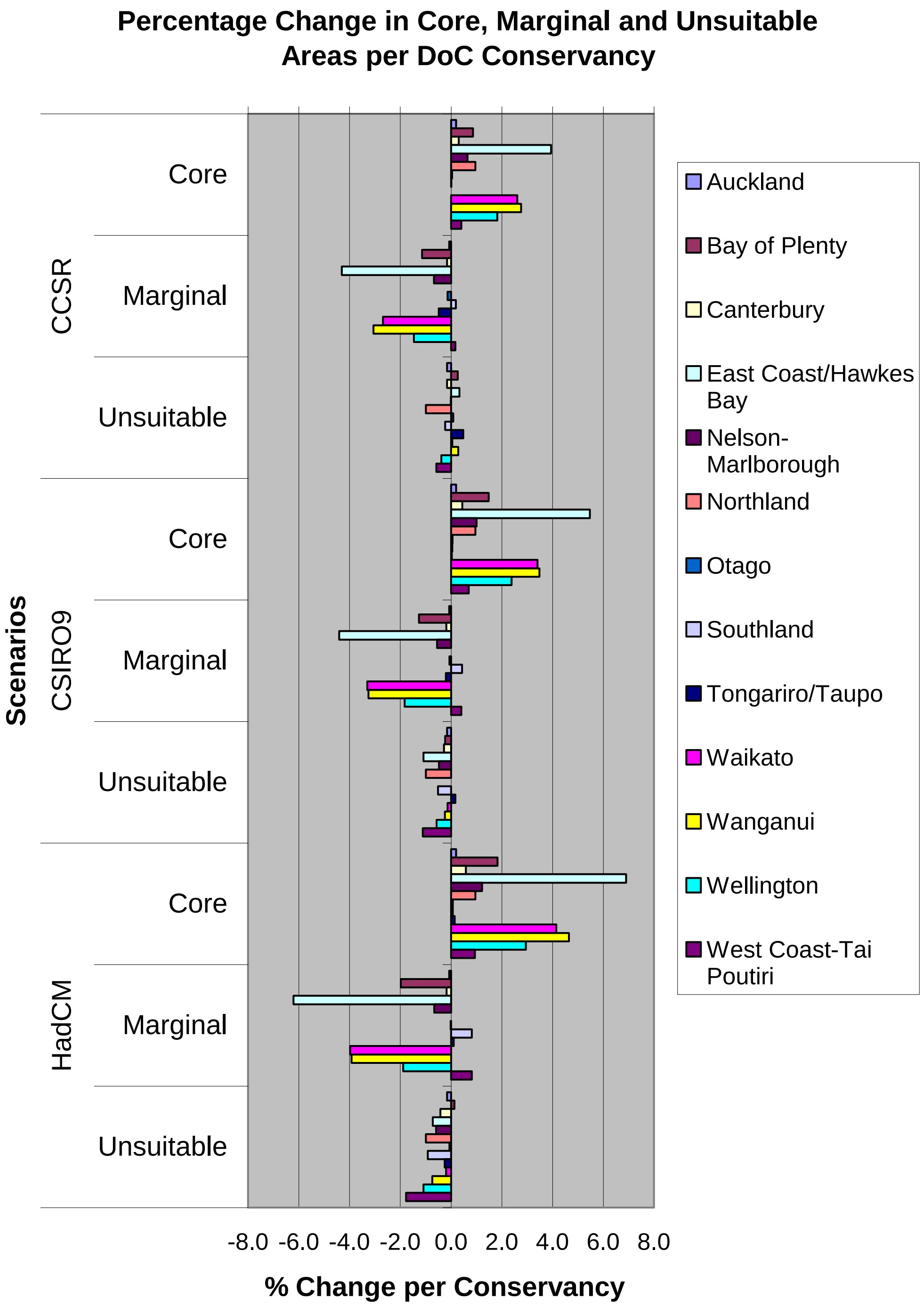


Figure 6.9 Percentage change in core, marginal and unsuitable areas per combined scenario and per DoC Conservancy at the national level.

Figures 6.10-6.12 are the ‘count maps’ for each of the combined scenarios. These provide a measure of the reliability of the extrapolated Habitat Suitability maps under each of the combined scenarios. As mentioned earlier, the more cells with values >1 the more reliable the extrapolated map. Using this rationale, the CCSR and CSIRO9:A1B-Mid combined scenario extrapolated outputs have the highest reliability, followed by the HadCM:A1FI-High map. The HadCM:A1FI-High map had -10 values, indicating that there were cells for which factor values had to be extrapolated as they did not fall within the range of EGVs in the baseline model. This is an expected result, given that under the HadCM:A1FI-High, both MTminJ-A and AWD had the largest perturbation, i.e. change in value range, and one would expect that more cells would fall outside the original baseline line range as a result.

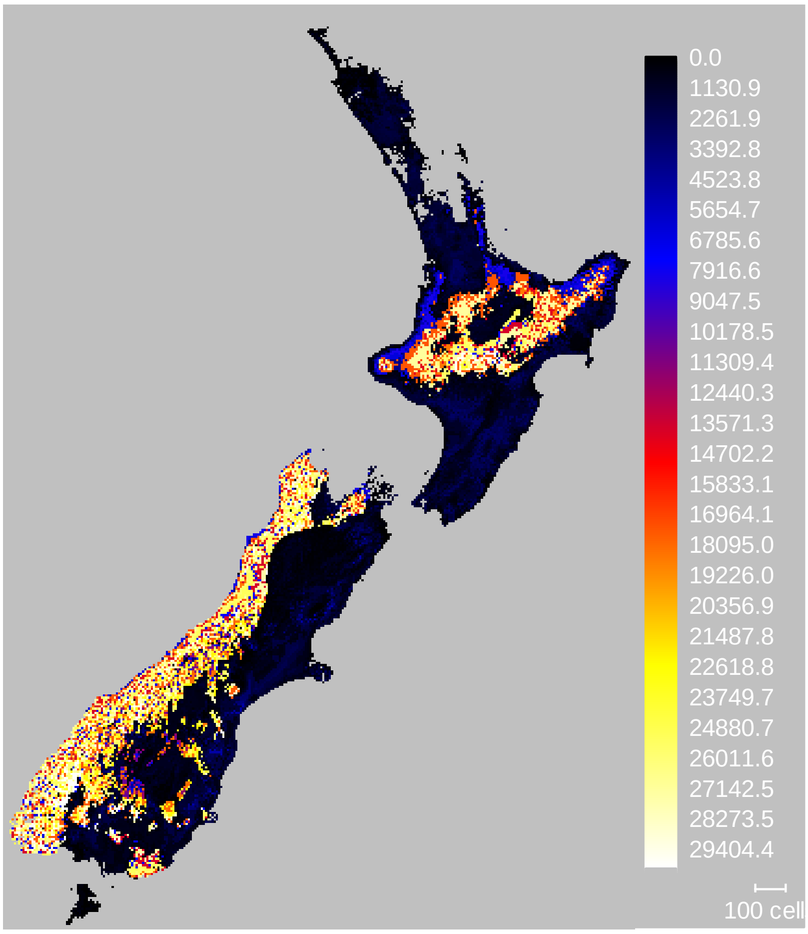


Figure 6.10 CCSR:B1-Low combined scenario for 2050, counts map.

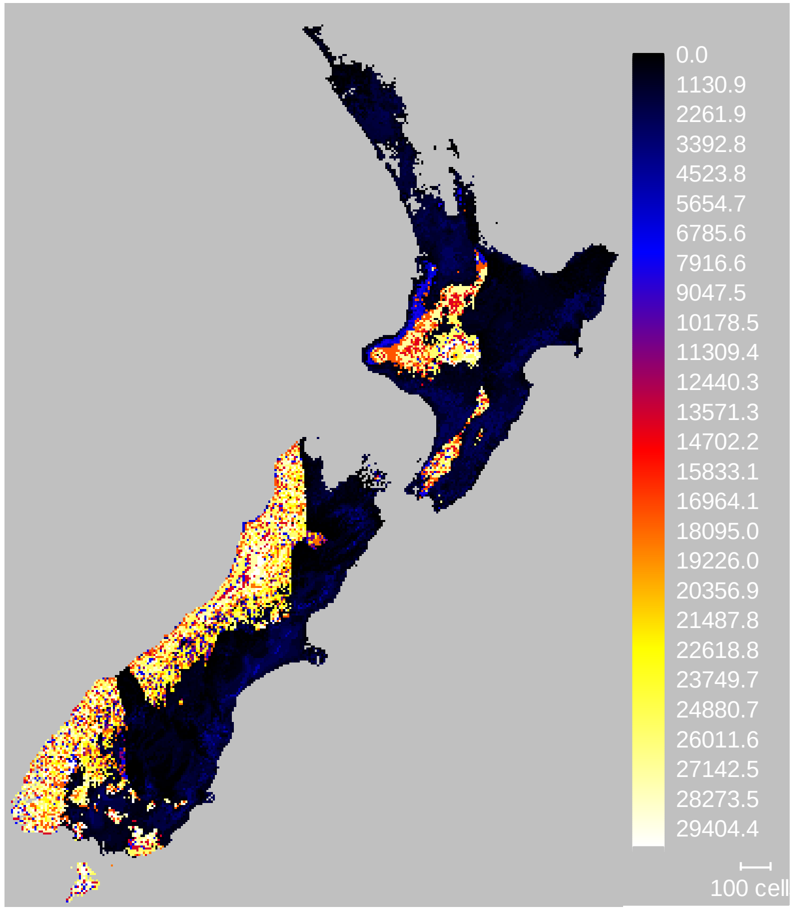


Figure 6.11 Darlam:A1B-Mid combined scenario for 2050, counts map.

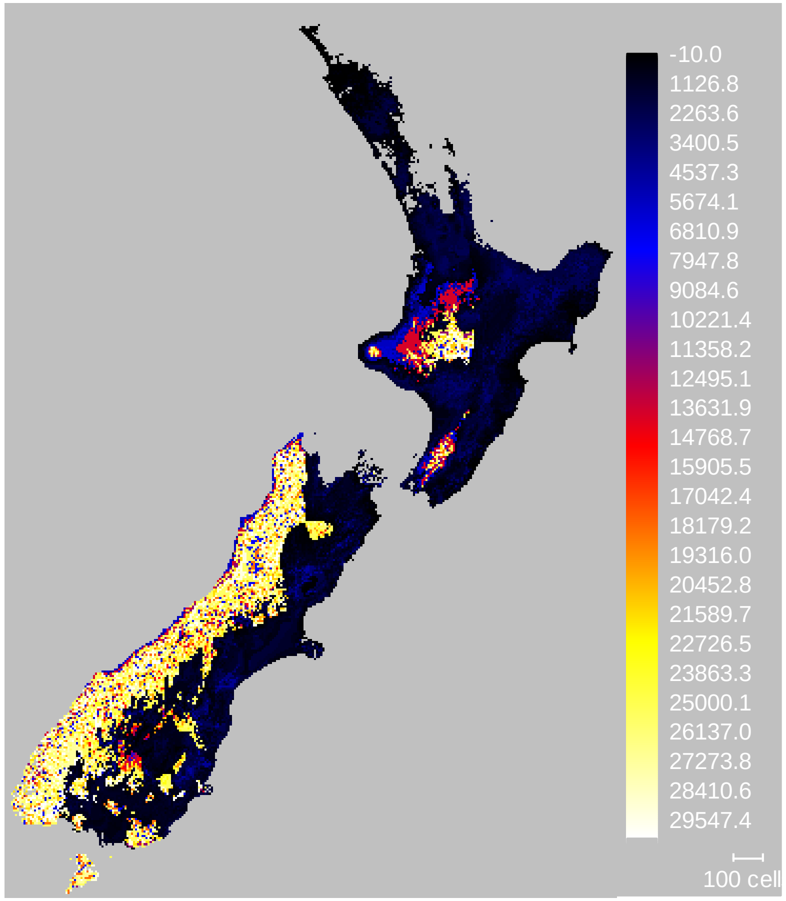


Figure 6.12 HadCM:A1FI-High combined scenario for 2050, counts map.

6.4 Results: landscape level species distribution of *T.fluminensis*

At the landscape level, the habitat suitability for *Tradescantia* increased under all three combined scenarios in the following order: CCSR:B1-Low+SmartGrowth > Darlam:A1B-Mid+SmartGrowth > HadCM:A1FI-High+Buildout. Figures 6.13-6.18 show the resulting combined future Habitat Suitability Maps. They show the changes to invasibility of the landscape based on the integration of:

1) MTminJ-A scenarios for the year 2050;
2) Proximity to urban growth scenarios for the year 2050; and
3) Proximity to streams (assumed to be the same under all scenarios).

The invasibility of the case study landscape increased under all future scenarios of projected climate and land use change. Using the extrapolation module of Biomapper, it was found that there were significant changes to the amount of core, marginal and unsuitable areas available to *Tradescantia* at the landscape level to the year 2050 (see Table 6.5). The change to invasibility was largest under the HadCM:A1FI-High MTminJ-A + Build-out urban growth scenario (Fig. 6.17). This was followed by the Darlam:A1B-Mid MTminJ-A + SmartGrowth urban growth scenario (Fig. 6.16), followed by the CCSR:B1-Low MTminJ-A combined + SmartGrowth urban growth scenario (Fig. 6.17).

Combined Scenarios	**% Δ Core Areas**	**% Δ Marginal Areas**	**% Δ Unsuitable Areas**
CCSR:B1-Low + SmartGrowth	+ 5	+ 6	- 11
Darlam:A1B-Mid + SmartGrowth	+ 8	+ 5	- 13
HadCM:A1FI-High + Build-out	+ 21	- 8	- 13

Table 6.6 Percentage change in core, marginal and unsuitable areas per combined scenario for 2050.

For each future integrated scenario, the highest invasibility scores were consistently located within 10-20 km of the coastal margin between Welcome Bay in the south east and the coastal township of Waihi in the north east. The other major change in suitability was in the upper reaches of the catchments inland between the coastal settlements of Katikati and Omokoroa, which resulted in a substantial increase in invasibility into the Kaimai Ranges. A similar increase in invasibility was recorded around the outer edges of the Kaimai Ranges inland from the large coastal city of Tauranga, under all scenarios. The long coastal strip of Papamoa showed the sharpest sensitivity to changes in the combined scenarios.

The only area which retained the lowest invasibility scores under both the baseline and future integrated scenarios was in the intact forest to the south west of the case study area. This area, well inland in the upper reaches of the hills behind Tauranga, was furthest from urban areas and also had the lowest temperatures for the study area. A second area which showed low invasibility scores under the CCSR:B1-Low+SmartGrowth and Darlam:A1B-Mid+SmartGrowth scenarios was in the dendritic gully network inland and west of Tauranga. Under the HadCM:A1FI-High+Build-out scenario, however, this area increased in invasibility markedly, compared to the baseline scenario.

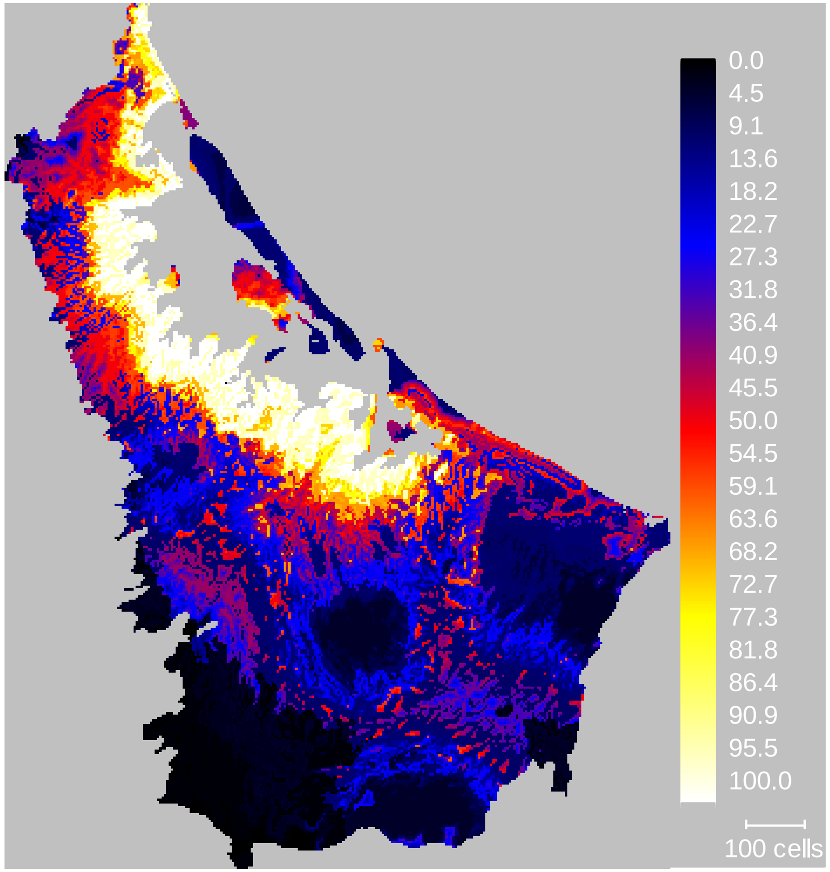


Figure 6.13 CCSR:B1-Low+SmartGrowth combined scenario for 2050 of the potential distribution of *Tradescantia*.

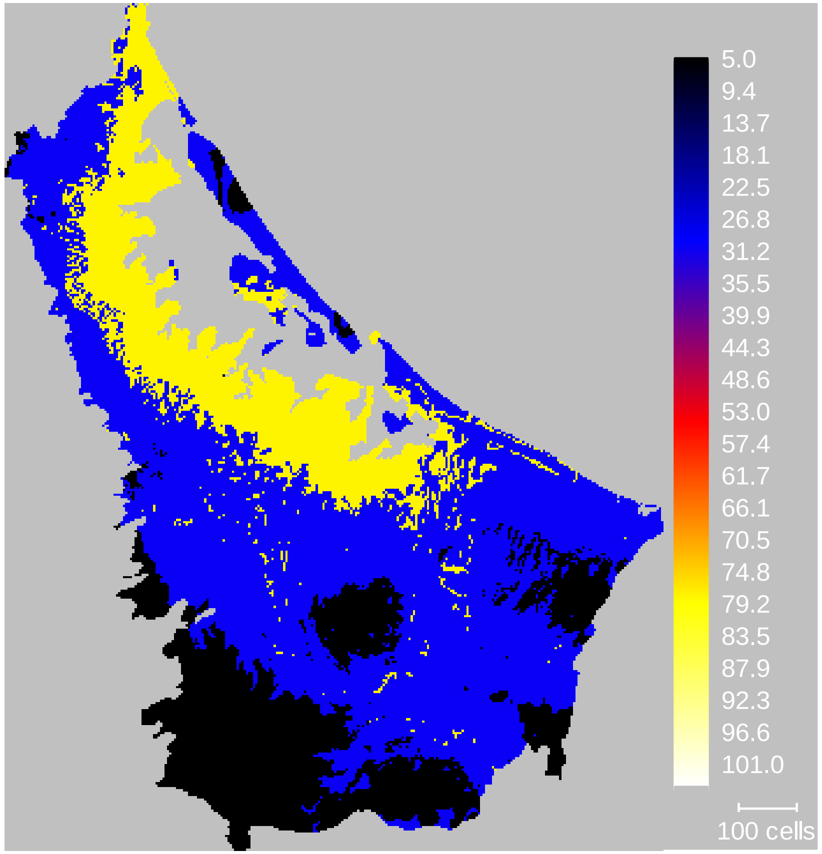


Figure 6.14 CCSR:B1-Low+SmartGrowth combined scenario for 2050: core, marginal and unsuitable areas. Greater coastal lowland suitability is projected.

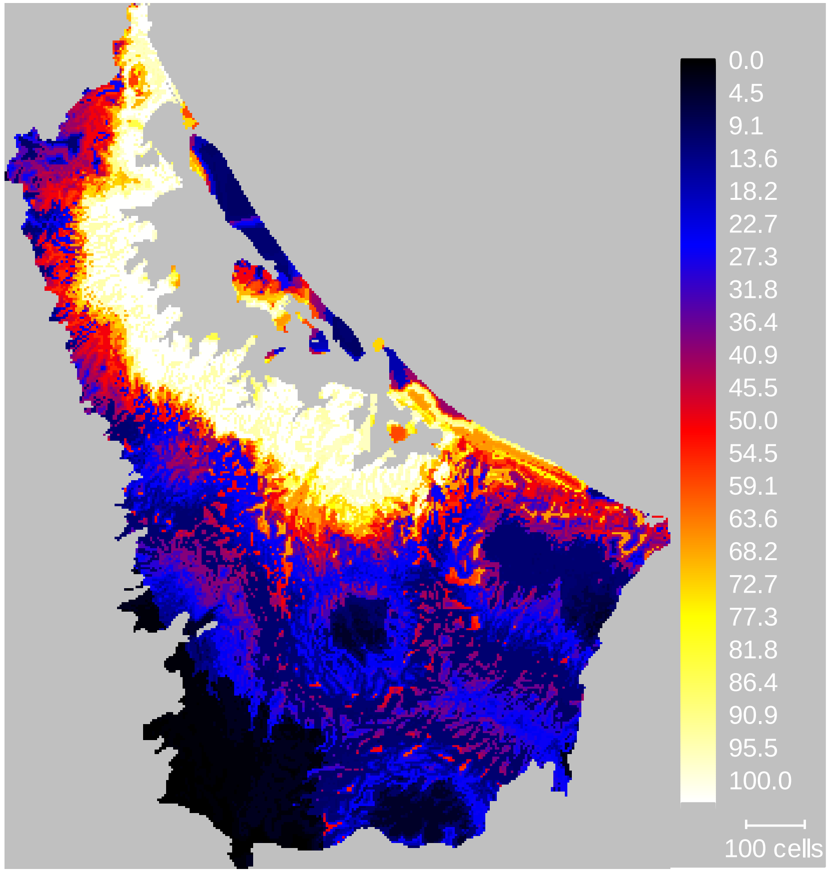


Figure 6.15 Darlam:A1B-Mid+SmartGrowth combined scenario for 2050 of the potential distribution of *Tradescantia.*

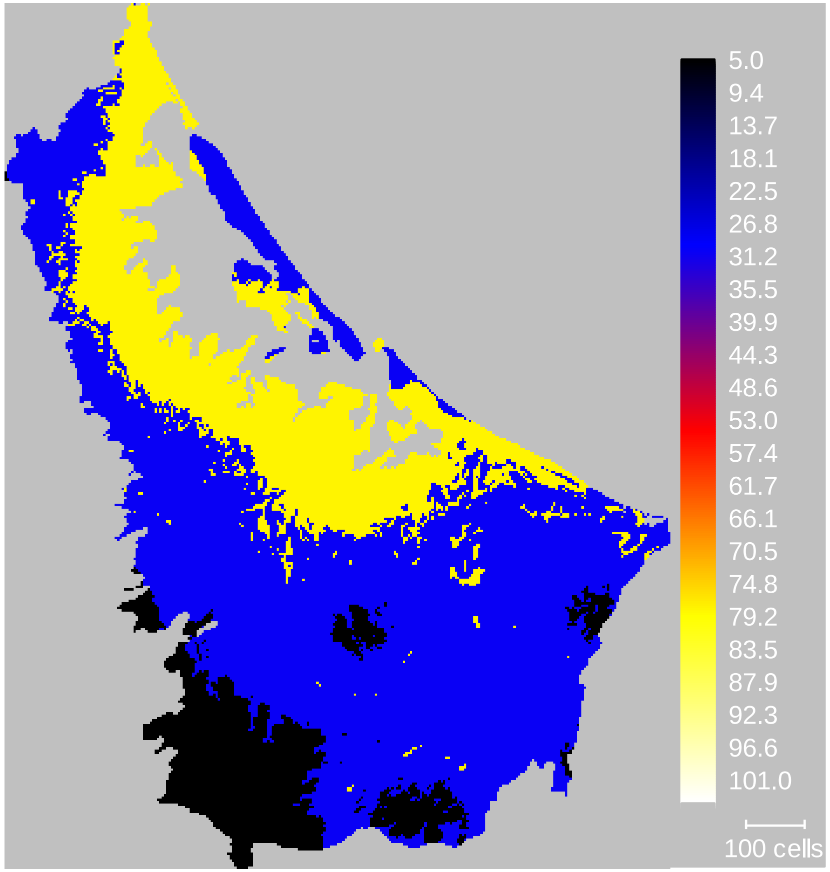


Figure 6.16 Darlam:A1B-Mid+SmartGrowth combined scenario for 2050: core, marginal and unsuitable areas. Greater coastal lowland suitability is projected here as well.

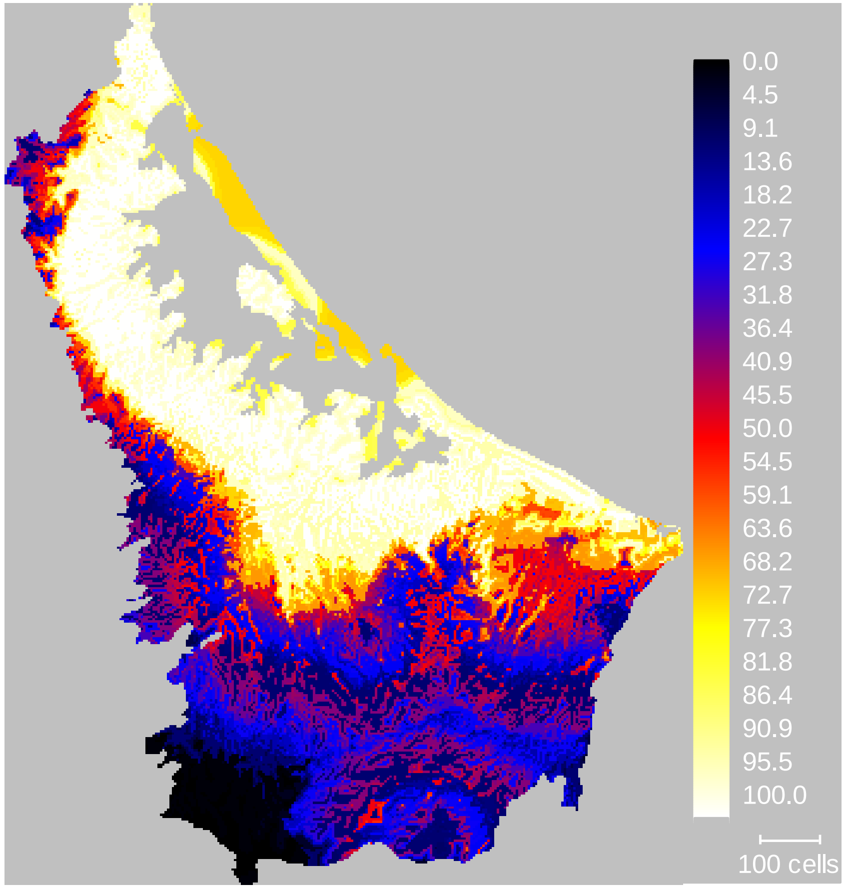


Figure 6.17 HadCM:A1FI-High+Build-out combined scenario for 2050, of the potential distribution of *Tradescantia*.

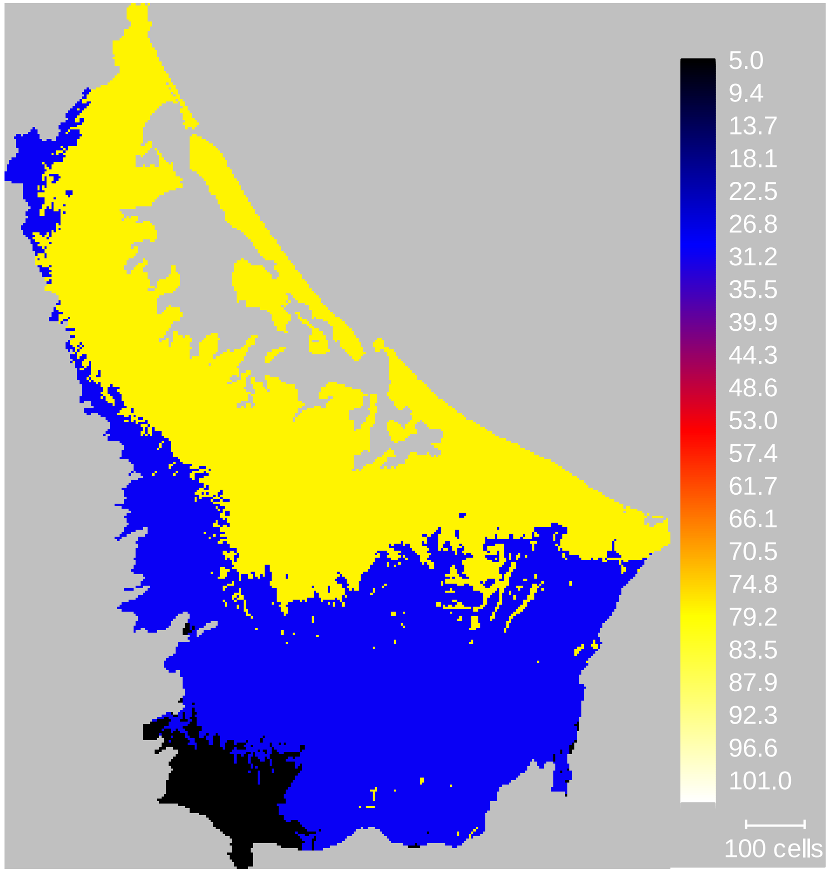


Figure 6.18 HadCM:A1FI-High+Build-out combined scenario, for 2050: core, marginal and unsuitable areas. Widespread lowland coastal increase in core area is projected.

Figures 6.19-6.21 are the count maps for each of the combined landscape extrapolated scenarios. The extrapolations at the landscape level show a marked increase in the number of cells which were extrapolated (rather than using the direct or interpolated factors from the baseline model), with the number of cells extrapolated decreasing order: HadCM:A1FI-High+Buildout > Darlam:A1B-Mid+SmartGrowth > CCSR:B1-Low+SmartGrowth. Therefore, the reliability of the resultant maps decreases in the following order: CCSR:B1-Low+SmartGrowth > Darlam:A1B-Mid+SmartGrowth > HadCM:A1FI-High+Buildout. Most of the extrapolated cells coincide with areas of urban growth under the SmartGrowth, and Build-out scenarios of LUC.

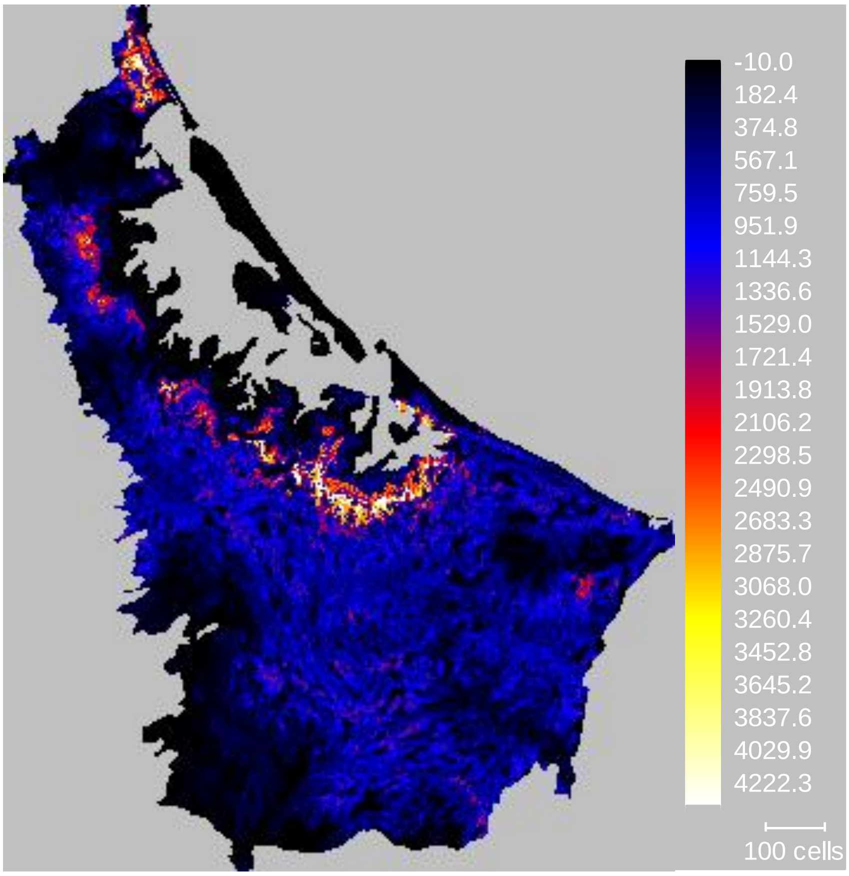


Figure 6.19 CCSR:B1-Low+SmartGrowth combined scenario for 2050, count map. The core areas as per Figure 6.14 are mostly extrapolated with count values =-10; while marginal areas are mostly derived from the original factor combinations with count values >0.

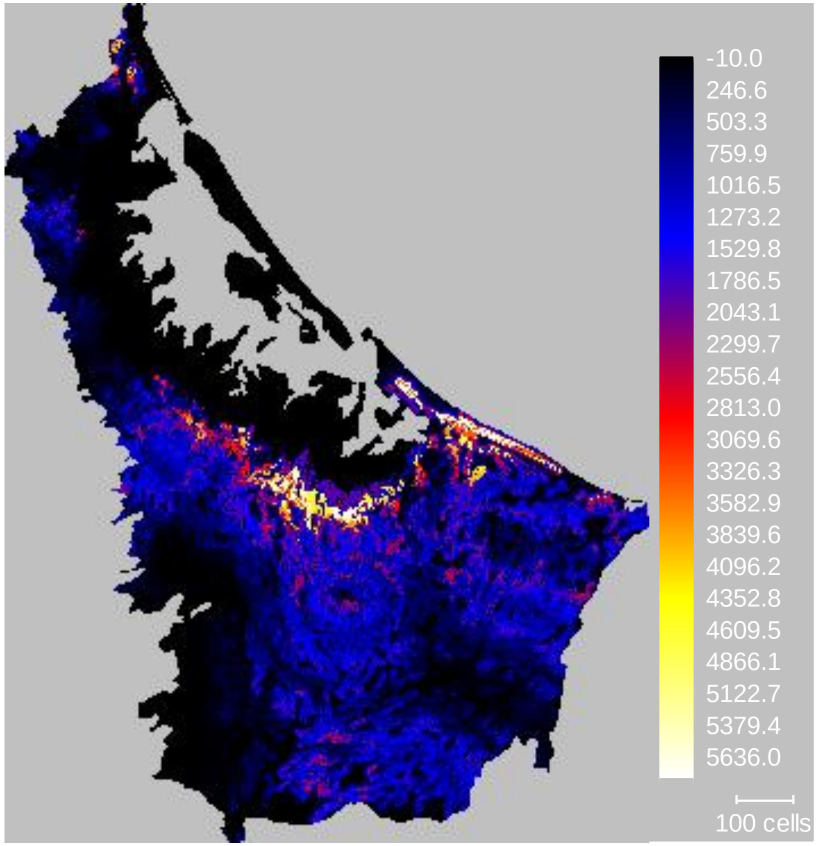


Figure 6.20 Darlam:A1B-Mid combined scenario for 2050, count map. The core areas as per Figure 6.16 are mostly extrapolated; while marginal areas are mostly derived from the original factor combinations.

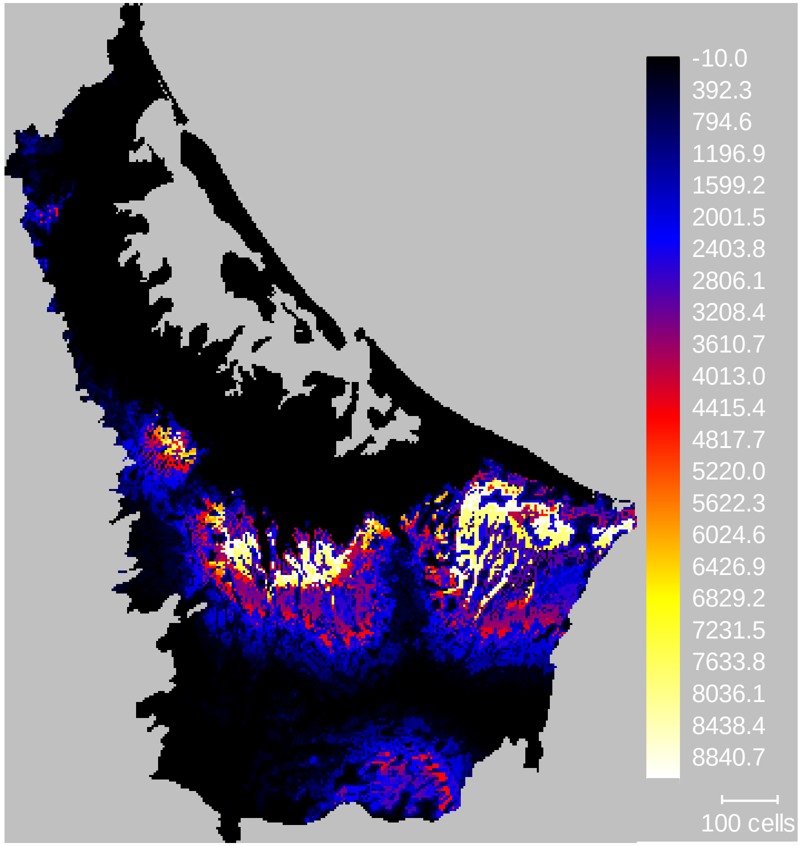


Figure 6.21 HadCM:A1FI-High combined scenario for 2050, count map. The core areas as per Figure 6.16 are mostly extrapolated; while marginal areas are mostly derived from the original factor combinations.

The changes to the projected distribution changes for *Tradescantia* were assessed in the various types of protected areas within the landscape. The protected area types ranged from DOC reserves to district and city reserves, sites of ecological significance and covenants. In addition to this, the scenarios for future changes to the protected area network included the replanting of the riparian network (described in Chapter 4) and areas of proposed new vegetation planting by Environment Bay of Plenty (Bay of Plenty Regional Council). The highest change was taken to be where the cell HS values were >50. Table 6.6 shows the results for the 8 protected area types. Therefore the results for these two categories over-represent the areas classed as 'Core' in the HS Map. The percentage change in area per protected areas is shown in Figure 6.22.

Protected Area Types	**Core Area HS: cell counts per Combined Scenario**			
	Baseline	CCSR:B1-Low + SmartGrowth (% Change from Baseline)	Darlam:A1B-Mid + SmartGrowth (% Change from Baseline)	HadCM:A1FI-High + Build-out (% Change from Baseline)
DoC Reserves	25208	192584 (76.3)	187200 (73.8)	177428 (69.4)
Riparian enhancement	101394	150555 (22.4)	153353 (23.7)	158740 (26.1)
EP Proposed Veg	1211	5658 (2.0)	5721 (2.1)	8795 (3.5)
WBoP Sites of Ecological Significance	1874	18573 (7.6)	19827 (8.2)	27827 (11.8)
WBoP Covenants	350	925 (0.3)	871 (0.2)	2073 (0.8)
WBoP Plan Changes	1531	16378 (6.8)	16965 (7.0)	22954 (9.8)
Significant Natural Areas - Tauranga	2184	1109 (-0.5)	3242 (0.5)	3249 (0.5)
QEII Reserves		368 (0.2)	515 (0.2)	655 (0.3)

Table 6.7 The change in core area cell counts per protected area type within the case study landscape.

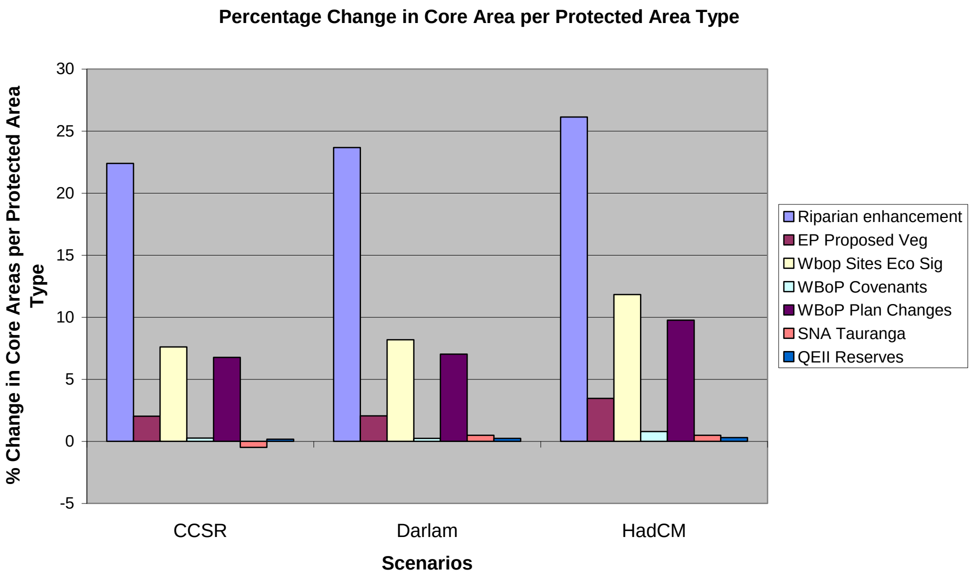


Figure 6.22 Percentage change in core area per protected area type for the Western Bay of Plenty and Tauranga.

Figure 6.22 shows that the highest changes in the number of 'core area' cells were in the WBoP Sites of Ecological Significance, the WBoP Plan Change areas and the Environmental Protection proposed re-vegetation areas. This shows that the potential risk to protected areas form *Tradescantia* into the future is projected to increase under all combined climate and land use change scenarios. The riparian enhancement planting will certainly be under risk if localized revegetated patches provide suitable ground space, shade and water dispersal and disturbance into the future. From a biodiversity management point of view this would be a threat to the habitat quality over the long-term, if Tradescantia were to invade or re-invade these highly invasible patches. Other protected area types will be more at risk depending on the size of the habitat patches (e.g. more at risk if <9ha) and in combination with a stream(s) that can disperse propagules from upstream infestations into these suitable sites. Therefore, it would ideally be recommended that upland sites be actively managed and eradicated where feasible, so as to reduce the re-invasion potential to patches further downstream. Current biocontrol trials may also eventuate in an adequate biocontrol species being identified which may increase the feasibility of reducing populations or their biomass over the long-run. Present research trials by Landcare Research NZ (Dr Simon Fowler and others): are looking optimistic of identifying one or more biocontrol agents.

6.5 Summary

This chapter produced the integrated scenarios which combined MTminJ-A and AWD at the national level (CCSR:B1-Low, CSIRO9:A1B-Mid and HadCM:A1FI-High scenarios); and MTminJ-A (CCSR:B1-Low, Darlam:A1B-Mid and HadCM:A1FI-High scenarios), Proximity to SmartGrowth/Buildout and Proximity to Streams at the landscape level. Both national- and landscape-level future combined scenarios were produced using the 'Extrapolation module' of BioMapper. Extrapolation models were produced using baseline EGVs and the extreme optimum medians algorithm, because the algorithm was able to extrapolate for species distributions where the species prefers extreme values of most EGVs (either high of low extremes). This was the case for *Tradescantia*, on most EGVs. The 'Extrapolation model' produced plausible future scenarios and provided a very useful modelling framework for integrating climatic and non-climatic landscape-level habitat and disturbance variables which are central to mapping the overall habitat suitability for an invasive species like *Tradescantia*.

All combined scenarios projected an increase in the habitat suitability/species distribution of *Tradescantia,* both the national and landscape levels, with the CCSR:B1-Low+SmartGrowth combined scenario showing the least change and the HadCM:A1FI-High combined scenario showing the greatest change to species distribution at both levels. Under all scenarios the 'core' area of the highest habitat suitability increased for all regions and for DoC conservancies at the national level. 'Marginal' areas typically decreased in all regions and conservancies, except for the West Coast and Southland where they increased slightly. At the landscape level, the 'core' area within each of the eight protected area types increased under each combined scenario. As a result it is likely that based on species distribution, both at the national and landscape levels, *Tradescantia* will have an increasing distribution in New Zealand, however the overall impact will be determined by a range of factors which will be further discussed in Chapter 7.

7 Chapter 7: The effects of climate and land use changes on *T.fluminensis*: major findings and conclusions

Chapter 7: The effects of climate and land use changes on *T.fluminensis*: major findings and conclusions

7.1 Introduction

This Chapter provides a discussion of the research undertaken in this thesis and of the major findings that emerged. The combined effects of climate change and land use change on *Tradescantia*'s distribution are assessed; the significance and implications of the research findings, for assessing the impacts of *Tradescantia* in New Zealand are discussed; the usefulness of the species distribution modelling for integrated assessment of combined effects is evaluated; limitations of the research and suggestions for future research are provided followed by the major conclusions of this thesis.

7.2 Summary of the research and major findings

Chapter 1 provided a review of the literature that drew together the various elements of climate change, land use change, invasive plant ecology and impacts, to focus on the major research question of this thesis: "What are the combined effects of climate change and land use change, on *Tradescantia fluminensis* in New Zealand?". This thesis set out to assess the combined effects of climate change and land use change on the distribution of *Tradescantia fluminensis* (Vell.) in New Zealand. Various species distribution models were compared and two were selected for use: BioCLIM and ENFA. Of the two, ENFA was chosen for the integration exercise because it had the following capabilities:

1) used 'presence-only' data for the distribution of the species;
2) most importantly: incorporated climatic <u>and</u> non-climatic data to model the spatial distribution at multiple scales, therefore, both climate and land use variables could be used from Chapter 2;
3) explicitly modelled the species-environment relationships to produce a baseline model and the spatial distribution map Chapter 3;

4) it can extrapolate the baseline model into the future using the scenarios (Chapters 4 and 5) to produce integrated future scenarios of the species distribution (Chapter 6).

In Chapter 2, the ecology of *Tradescantia* was reviewed and key associations with climate, habitat, landscape and disturbance-related variables were identified for the species distribution modelling and scenarios-building exercises of Chapters 3-6. This highlighted that *Tradescantia fluminensis* is a persistent and high impact environmental weed of natural and disturbed areas in New Zealand. Any environmental or human drivers that significantly enhance the suitability for this weed beyond its current distribution and promote its invasive spread pose a threat to conservation into the future. It was noted that the full impacts of *Tradescantia* in native ecosystems is yet to be fully realised in New Zealand (Standish et al., 2001). Given its various ideal traits as an invasive species, the environmental persistence of this weed will continue to degrade fragmented habitats in the absence of effective control measures. The long-term consequences of impact on indigenous biodiversity from this species, particularly in degraded habitats which are already at risk is of particular concern from a conservation point-of-view and provided a useful context for this study.

Chapter 2 concluded that *Tradescantia* was an ideal case study species for the assessment. One of the main limitations of modelling invasive species distribution with climate change is that many invasive species are still in the process in invading their realised novel ranges where they have been introduced (i.e. outside their native ranges) (Hirzel, 2002). When this is the case, modelling the realised distribution of a species, based on distribution data available for the introduced range, is likely to produce a potential distribution range (equivalent to the Baseline distribution for this assessment), that is much smaller than its potential range. At the national level in New Zealand, however, *Tradescantia* has established in a wide range of habitats, and has expended to the full latitudinal range of New Zealand, i.e. from Northland in the north to Stewart Island in the far south, mainly because of humans planting it. This was one of the main reasons why modelling *Tradescantia* at the national level would produced more reliable results, as the realised distribution is expected to be similar to the potential range for the Baseline distribution.

Tradescantia was ideal for modelling also because its dispersal pathway is linked with people movements and settlement patterns which represent the primary source populations for *Tradescantia* in most landscapes. This was an advantage in terms of linking it to future scenarios of land use change through changes to urban extent. Since *Tradescantia* reproduces by vegetative means, it is not reliant on other species, like birds, for dispersal. This would have important implications for the modelling exercise, because inter-specific interactions would need to be taken into account in the modelling exercise. For example, in one of the only studies to look at climate change effects and species interactions in species distribution modelling, Araújo and Luoto (2007) found that biotic interactions could be represented by adding the geographic distribution of other species which the focal species relied on, as explanatory variables. This significantly altered the explanatory and predictive power of the bioclimatic models at macro-ecological scales (e.g. at the European continental scale). However, in their case the modelled species was a native butterfly which relied specifically on a few tree species of the genus *Corydalis* for its larval development. No inter-specific relationships of this sort are known for *Tradescantia* (apart from humans), and is perhaps related to its less specialised ecological niche.

The reader will recall that in Chapter 3, various species distribution models were compared and evaluated for their suitability for this study. This study confirmed what the literature suggested, that ENFA has the ability to explore the species-environment relationships of multiple variables (through the EGV score statistics), in generating the species habitat suitability, and it is possible to determine the individual contributions of each of these variables to the explanatory marginality and specialisation factors which were used to derive the habitat suitability model for the species of interest. Because of this capability in ENFA, it was possible to refine the selection of variables and the scale at which modelling was appropriate which was very useful (Hirzel et al., 2001).

Having selected the appropriate modelling approach and produced that baseline distribution for *Tradescantia*, Chapters 4 and 5 subsequently built scenarios of the perturbed land use and climate variables. As the reader will recall, in Chapter 4, two alternative land use change scenarios were generated at the landscape level in addition to the baseline scenario: (1) the SmartGrowth Scenario and (2) the Build-out Scenario; each highlighting alternative urban growth and associated road network changes, and vegetation changes. These scenarios were based on a process-based approach to scenario-development. It was noted that the most important components of the land use change scenarios were that they should represent changes to suitable habitats (i.e. urban areas and various riparian vegetation classes); disturbance sources and dispersal pathways. In Chapter 3, the land use related variables that were found to contribute to the spatial distribution of *Tradescantia* were: proximity to urban, proximity to streams, proximity to roads, frequency of riparian woody vegetation, frequency of non-riparian woody vegetation, frequency to non-riparian herbaceous vegetation, and frequency of riparian herbaceous vegetation. In developing the LUC scenarios, this provided the rationale to perturb the baseline layers in such a way that they represented alternative future spatial extents for each of the above LUC variables. The SmartGrowth Strategy of the Western Bay of Plenty-Tauranga provided one of New Zealand's best examples of an in depth spatial land use planning exercise, to a time horizon of 2050. It was based on population projections and a sub-regional strategy for allocation of projected urban growth. The sub-region is committed to this in terms of infrastructure developments, protection of landscapes for food and fibre, and the protection of significant natural areas and landscapes et cetera. This provided a suitable spatial planning context for which to create both the SmartGrowth urban scenario, as well as the backcasted Build-out scenario, as a variant. Chapter 4 brought to the fore that environmental enhancement was a key priority in the region that would modify existing areas of indigenous biodiversity. This 100% restoration target assumed the following:

1) EBoP, landowners and other partners will be committed to the 100% restoration target, through to completion; and
2) significant amounts of extant riparian woody vegetation are not removed.

Both of these assumptions affect the connectivity and corridor effect of the riparian habitat at a landscape-level and its role in facilitating the persistence and spread of *Tradescantia* at the landscape level.

The Build-out scenario tested the sensitivity of increasing the urban areas to a maximum under current urban suitability zoning. Under such a scenario, it was plausible to suggest that due to the high urban pressure for development, the 100% target for riparian restoration would not be met by the sub-region, particularly in the urbanised areas; and also from landowners who may not be willing to replant riparian strips on their land. This was reflected in the riparian scenario by reducing the area of riparian herbaceous vegetation converted to riparian woody vegetation by 2050.

Chapter 5 focused on the climate change scenarios which were generated at the national and regional levels. AOGCMs were selected to be the most appropriate method to develop both the future climate and climate change scenarios. While the change scenarios provided very useful information in interpreting where the highest and lowest changes were taking place under each GCM pattern for each of the variables, it was the future climate scenarios which were used in the ENFA analyses.

The integrated modelling methodology is valuable in assessments of impacts from species distribution/range change, both with and without climate change and/or land use changes. This is the primary objective in developing the integrated assessment methodology and ties together the relationships between *Tradescantia*'s distribution and multiple climatic, land use and landscape variables into a single spatially-explicit modelling system for comparing the impact under baseline and future scenarios. This represents the 'sensitivity analysis' under various 'what if' conditions. The integrated methodology is, therefore, evaluated based on the efficacy of conducting a spatially-explicit sensitivity analysis given the available data, and whether it is helpful to decision-makers (biosecurity pest control staff, policy-makers and planners) in examining the impacts under various plausible pre-determined scenarios of climate changes and land use changes. In addition, this evaluation serves as a basis for future improvement or development of this trial methodology, in particular for its usefulness in assessing the impacts for other invasive species. The following sections will assess the combined effects of climate change and land use change, based on the results of Chapter 6. The model evaluation will specifically discuss the development of the methodology and its performance.

7.3 Assessment of the combined effects of climate change and land use change on the distribution of T.fluminensis

The integrated assessment methodology was developed to be species-specific, incorporating aspects of both the species invasiveness and habitat invisibility in developing spatially-explicit variables in ENFA. The resultant species distribution maps were a measure of the 'impact' of *Tradescantia* at the national and landscape scales. By integrating spatially-explicit scenarios for climate change or land use change scenarios, it was possible to explore the impacts of many possible combinations or 'what if' scenarios along with landscape level factors. Scenarios can be assessed on their own or in combination, against the baseline scenario. The output of the models is a spatially-explicit **'habitat suitability index'** which could be compared for each scenario or combination of scenarios. These results could also be compared with baseline conditions to measure the changes quantitatively, by administrative area or protected area boundary, for instance, which is informative to resource managers and decision-makers. This makes the outputs easy to use and interpret for users who may not have any prior knowledge of the modelling approach. The following Sections 7.3.1 and 7.3.2 assess the national and landscape level effects respectively on *Tradescantia*.

7.3.1 Climate change effects on *T.fluminensis* at the national level

At the national level, four key findings emerged from this study, which are discussed in this section.

1. ***Climate change is projected to increase the habitat suitability for Tradescantia in New Zealand, under all three scenarios of climate change.***

The order of increase in habitat suitability or species distribution range is as follows: CCSR:B2-Low < CSIRO9:A1B-Mid < HadleyCM:A1FI-High. For each of the three combined scenarios, areas of core suitability increase, marginal areas change variably, and unsuitable areas are reduced in all administrative areas on both the north and south islands of New Zealand. Therefore, climate change will potentially shift the gradient of habitat suitability for this species in New Zealand, and effectively expand the potential species distribution. This effect is more pronounced for the North Island than for the South Island. In the South Island, core and marginal areas are restricted to the lowland coastal margins. There is also distinct latitudinal and altitudinal differentiation across the north and south islands in terms of habitat suitability and therefore, the realised distribution, under all three climate change scenarios tested. This result confers with results of assessments done on other invasive species in novel environments where their realised ranges are expected in to increase with climate change, particularly for species tested in Australia for instance (Kriticos, 2003 a and b).

2. ***This analysis shows that there are distinct increases in core areas of habitat suitability and decreases in unsuitable areas for Tradescantia across New Zealand.***

The ENFA extrapolations showed distinct increases in the core or highest suitability classes of the species realised distribution of *Tradescantia*, and declining marginal and unsuitable areas, particular in the North Island of New Zealand. On the South Island slight increases in core areas were projected, especially for the West Coast and Kaikoura Coast and further south from Christchurch to Dunedin. Apart from this distinct increase in Habitat Suitability on the coastal margins of the South Island and inland from Nelson and the Marlborough Sounds, the vast insular South Island is projected to remain largely unsuitable for *Tradescantia*, based on these extreme climatic constraints. On the West Coast and in Southland opposite changes to ‘marginal’ habitats compared to other areas: whereas everywhere else in the country, marginality was decreasing because marginal areas are becoming core areas, on the West Coast and in Southland the unsuitable areas are becoming marginal, in other words this is where the ‘southern boundary’ of *Tradescantia*’s range is likely to be expanding with climate change. The use of these newly marginal areas by *Tradescantia* will depend of propagule supply. The report by Williams and Hayes (2007) states that *Tradescantia* is common in forest margins as well as riparian forests and in gardens from Karamea to Hokitika on the West Coast (Hokitika being the largest urban centre south on the West Coast before the Haast Pass). Hence even though it represents parts of the southern range edge of *Tradescantia* in New Zealand it is still quite abundant in the areas where it grows along the West Coast (see Figure 7.1).

If -4^{o}C is taken to represent the theoretical ‘fundamental distribution range’ of *Tradescantia*, then the baseline ‘realised distribution’ of *Tradescantia* while geographically very similar, does not yet completely fill the theoretical fundamental range. This means that potentially *Tradescantia* can occur further inland and upland than the modelled ‘realised distribution’ suggests. The spatial location of the -4^{o}C boundary is projected to change under each scenario of climate change. However, this theoretical boundary may also be linked to frost occurrence and frost damage, which may take on a more locally variable pattern at a landscape level. Climate change is also projected to reduce the number of frost occurrences across the country. In order to test the sensitivity of *Tradescantia*’s distribution to frost occurrence, it would be necessary to do a more small-scale study that incorporates frosts events and changes to their return periods, based on individual climate station data (frost being an extreme cold event).

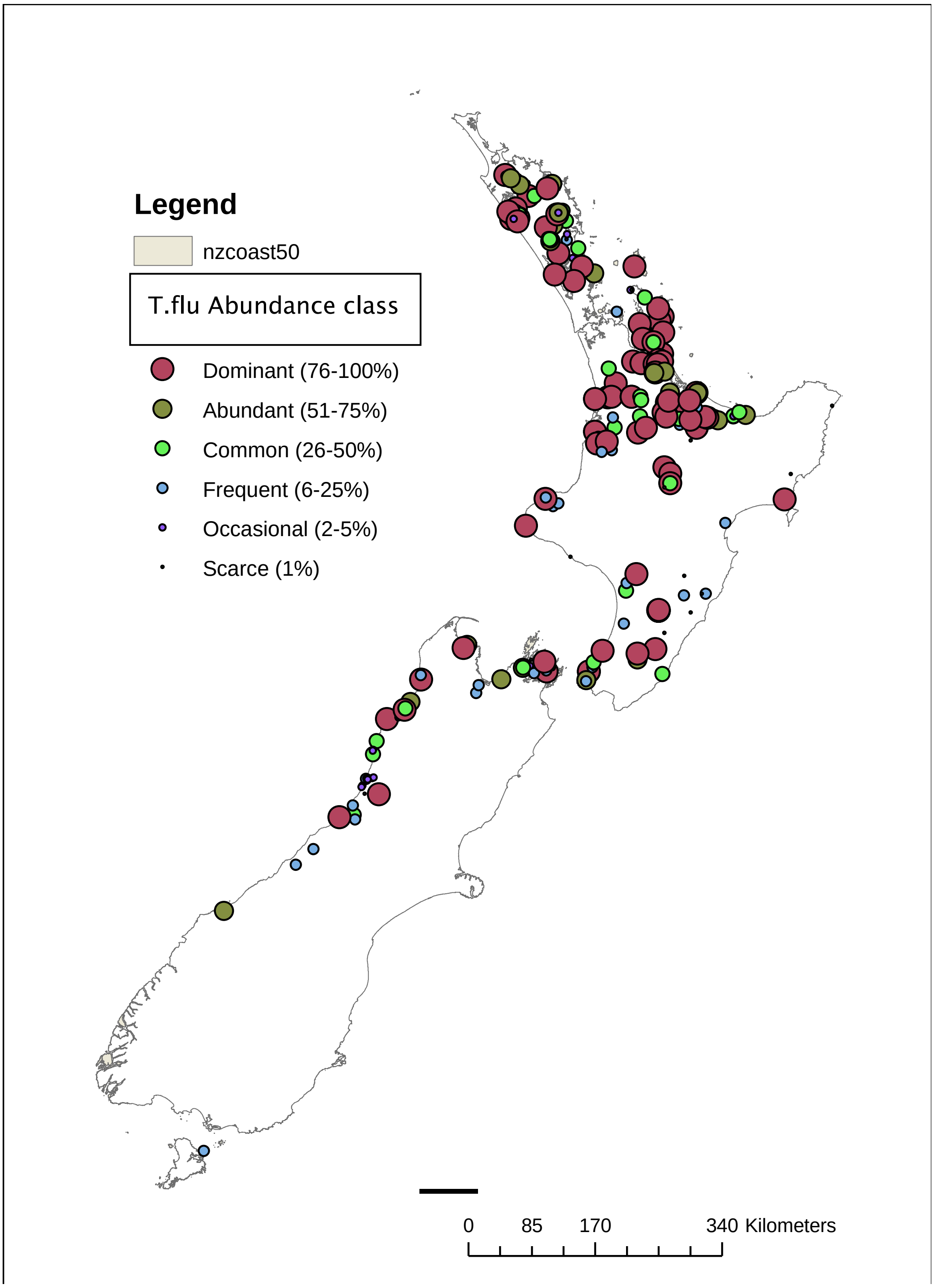


Figure 7.1 This map shows the abundance of *Tradescantia* in various locations across New Zealand. (Note that it represents the abundance for only a subset of the full number of presence observations).

3. ***At the national level, Minimum Temperature (July-August) and Annual Water Deficit were effective stress-related limiting variables in delineating habitat suitability and realised distribution.***

MTminj-a was the variable that contributed primarily to explaining the broad habitat suitability gradient for *Tradescantia*, in terms of core, marginal and unsuitable areas. It served as a direct explanatory variable. Annual water deficit was poor at explaining the broad habitat suitability, however, contributed largely to explaining the niche specificity at the national level, in that it delineated areas where Tradescantia was excluded from. While this may be linked to some level of drought-sensitivity by *Tradescantia* in extreme annual water deficit areas, it is much more likely that this was a result of these areas also concomitantly being areas where vast clearance of indigenous vegetation has occurred in extensive agricultural plains, hence removing suitable habitat. Therefore, it is likely that annual water deficit served as an indirect explanatory variable at the national level. Theoretically, it was expected that in areas where MTminJ-A $\leq 4^{o}$C and where there was very high annual water deficit, either separately or in combination, that these areas would be unsuitable for *Tradescantia*. This was found to be true. At the national level, model quality was very high (CBI≥0.86, ExS and ExS=1.0), giving high confidence that the models produced using MTminJ-A and annual water deficit explained the realised distribution of *Tradescantia* in New Zealand on climatic limits very well. Since the baseline model was based on variables which described the extreme boundary of the realised spatial distribution well, this was of benefit when perturbing those variables to produce future scenarios for the extrapolated models (CCSR:B1-Low, CSIRO9:A1B-Mid and HadCM3:AIF1-high scenarios), as it gave more confidence that they would be reliable indicator variables when extrapolating to the future.

There may also be other variables that affect the optimal suitability (i.e. that help to discriminate the higher suitability classes), if they are causally linked to *Tradescantia*'s physiological responses, growth and survival. However it was decided that MTminJ-A performed very well, also given it physiological linkages to *Tradescantia* via frost occurrence and frost damage. Available soil nitrogen (or nitrate) would also have been a useful variable to explore, however, the literature suggests that this would be more important as a causal variable at the local level, when the response/dependent variables are the either 'abundance' and/or 'relative growth rate, RGR' rather than 'presence' of *Tradescantia*. Another variable used in species-climate relationships is Growing Degree Days, however, for this variable also, the usefulness would have been minimal, given that it is usually used in conjunction with species which show a distinct phenological cycle and reproduce through seed set and fruiting. Since, *Tradescantia* reproduces solely by vegetative means in New Zealand this variable was not explored in the analysis. Therefore, in a final assessment, without further experimental studies which test *Tradescantia*'s growth and survival against specific variables, it can be said that MTminJ-A and Annual Water Deficit were good variables to have chosen to explain the species distribution and they performed very well in the models.

4. ***The ability of Tradescantia to occupy upland and inland areas in projected future scenarios, will depend on the availability of suitable habitat, disturbance sources and the dispersal limitation experienced in fragmented landscapes. To assess these factors, landscape-level analyses are required.***

Under all three projected future scenarios, the trend is for areas further inland and further upland to increase in suitability for *Tradescantia*. Typically, these are areas with less human pressure, and therefore, will present a dispersal limitation to *Tradescantia* unless further inland and upland settlement occurs. Given that it is now illegal for people to propagate or sell this species, human dispersal will be much less likely through garden planting (though not ruled out altogether through illegal garden waste dumping). Therefore, one would expect that natural dispersal would dominate, aided by other dispersal agents such as cattle at a localised level. The ability to occupy various habitats or land use / land cover types will assist in its long-term persistence at the national level, particularly in low to midland areas. Large geographic barriers to dispersal at the national level including the Central

Plateau on the North Island and the Central Axial Mountain Range on the South Island, will relatively rule out *Tradescantia* invading these dominant, insular, inland areas. Landscape level analyses were needed to assess the influence on suitable habitat types, disturbance and dispersal mechanisms which are treated in the next section.

7.3.2 Combined effects of land use change and climate change on *T.fluminensis* distribution at the landscape level

There are six key findings that emerge from the landscape level assessment and these are discussed here in this section.

1. ***At the landscape scale, land use change and climate change, in combination, will increase the invasibility and potential distribution of Tradescantia.***

Under all scenarios of land use change and climate changes tested, the potential invasibility and species distribution of *Tradescantia* will increase at the landscape level, in Western Bay of Plenty and Tauranga.

2. ***Furthermore, at this scale, land use contributes more to the distribution of Tradescantia than minimum temperature (July-August), and so it is anticipated that land use change will contribute more to the future potential distribution than climate change per se.***

Urban expansion and MTminJ-A will potentially increase the broad invasibility (marginality) of the landscape to spread by *Tradescantia,* followed by a further increase in invasion into habitats such as riparian woody (specialisation) of the spread of *Tradescantia*. This effect is of particular significance, given that under both land use change scenarios tested the extent and amount of riparian woody habitat and its spatial connectivity will increase, forming a vulnerable dispersal-disturbance-habitat-corridor. This land use change is of particular concern from the point of view of increasing invasibility at the landscape scale.

This finding applies to the Western Bay of Plenty and Tauranga and while many of the species-environment relationships, may hold true in other landscape also, this would need to be tested, by doing ENFA in these landscape to assess the various EGVs and their contributions to the factors (as per Chapter 3), rather than assume that the exact same relationships apply everywhere.

3. *The Habitat Suitability maps produced at the landscape level were sensitive to the spatial resolution selected, and to the variables selected at each spatial resolution.*

The various model runs at the landscape level, in Chapter 3, gave some interesting insights into spatial resolution (or scale) effects, the variables influencing the species distribution and the contribution of each of these variables (climate, habitat and disturbance) to the spatial distribution of *Tradescantia*. The reader will recall that two spatial resolutions were tested (15m x 15m and 50m x 50m). The ability to highlight the ecological niche specialisation of *Tradescantia* at the landscape level, was better at 15m x 15m and more variables could be used (up to 8). While the optimal scale for integrating riparian habitat within the modelling framework in ENFA was 15m x 15m, this fine resolution was impractical for producing the future scenarios of the landscape level invasibility, due to very high computation requirements at this scale, with eight explanatory variables in the extrapolation exercise. Also, at such a fine resolution the regional climate change scenarios used in generating the scenarios would be insufficient in representing the microclimatic gradients that would dominate suitable habitats at a resolution of 15m x 15m, for which future climate scenarios cannot be built. Therefore, in selecting an optimal baseline model for extrapolation in Chapter 6, it was essential to select those variables which made higher contributions to the first factor, i.e.

the Marginality Factor, over the inclusion of multiple variable which explained the multiple ‘Specialisation Factors’, at a scale of 50m x 50m. However, this increase in spatial resolution and number of layers reduced the ability of the model to extrapolate into the future using the future scenarios of those baseline layers (due to high processing requirements). As a result it was necessary select between the following scale-related trade-offs:

1) either reduce the number of variables used and retain the resolution of the analysis, at 15m x 15m; or
2) reduce the number of variables, and retain only those that could be represented at a larger resolution of 50m x 50m. This option was chosen, because it was decided that to retain the analysis at a 15m x 15m resolution for the sake of the riparian habitat data, it would be necessary to include microclimatic gradients instead of the regional MTminJ-A data layer that was available.

Therefore, this study highlights the influence of scale-effects on species distribution modelling. The 15m x 15m scenarios of future riparian habitats, though they could not be integrated into the extrapolation of the future habitat suitability or species distributions of *Tradescantia* directly, they were subsequently used in the post modelling exercise of quantifying the amount of change to core, marginal and unsuitable areas that had occurred under each of the integrated landscape level combined scenarios (based on proximity to urban, MTminJ-A and proximity to streams).

On the issue of spatial resolution, it is recommended therefore, on the basis of the results on this study, that a spatial scale be selected that matches the regional climate data and the other variables that make the highest contribution to the spatial distribution of the species (in this case proximity to urban). When using ENFA, it would be safe to select variables therefore that contribute more to the ‘marginality’ of the species rather than the ‘specialisation’ if a trade-off has to be made on the basis of how many and which variables to retain in the model at a particular spatial resolution.

As a result the integrated CC+LUC scenarios in Chapter six chose the variables which best explained the global marginality, i.e. contributed the most to the Marginality of First Factor. Of the two, marginality and specialisation, the more important one to retain in the Marginality Factor or the first factor, given that it explains the how the species habitat differs from the average conditions available (based on the explanatory variables selected to do the modelling exercise. As a result, at both the national and landscape levels, the extrapolated future combined scenarios are based on the explanatory variables that explained the species marginality and as a result they do not pick up the finer scaled habitat suitability, that were evident in the model which were created at a scale of 15m x 15m at the landscape level.

4. *Based solely on the criterion of the 'Count Map', the reliability of the future extrapolated habitat suitability maps was higher at the national level than at the landscape level.*

The actual model qualities for the extrapolated models using the combined ENFA scenarios cannot be fully measured, for the reason that the realised distribution for *Tradescantia* in the future is unknown. However, based on the 'Count Maps' produced by the Extrapolation Module of , the reliability of the future habitat suitability maps decreased as the projected climate changes increased from the Baseline. This was because more cells were outside the upper maximum value of the Baseline range both for MTminJ-A and annual water deficit. At the national level, the percentage of cells that had to be extrapolated was quite low, 1% for both CCSR-B2-Low and CSIRO9:A1B-Mid combined scenarios, and 4% for the HadCM3:A1FI-High combined scenario; meaning that the extrapolation were 99% and 96% based on the original factor combinations for cells from the Baseline model, when generating the future Habitat Suitability Map. This is a very good result for model reliability, in terms of the extrapolation procedure from the Baseline, however as mentioned earlier it is not a measure of the predictive accuracy for the realised distribution of *Tradescantia* by 2050. At the landscape level the extrapolation percentages from the Baseline were very different to the national level. The CCSR:B1-Low combined scenario required an extrapolation percentage of 5%, Darlam:A1B-Mid 16% and HadCM3:A1FI-High 35%. The extrapolation percentage was in all three cases, estimated on the basis of the MTminJ-A '% coverage' value which indicated what margin of extrapolation was required. The highest values of MTminJ-A in the future scenarios, fell outside the upper maximum of the Baseline MTminJ-A range, and were optimal for *Tradescantia*. These also corresponded to areas which had the highest habitat suitability scores when combined with 'Proximity to urban' and 'Proximity to streams'.

5. The ENFA Extreme Optimum medians algorithm (or Veronika's algorithm) was particularly suitable for modelling Tradescantia.

Tradescantia occupies an extreme optimum at the lowest values of all proximity variables: proximity to urban, proximity to roads and proximity to streams (i.e. where in greatest proximity, expected highest suitability) classes. This was also true with respect to MTminJ-A. This is because the location of urbanised areas within most landscapes will be predominantly coastal, and therefore will typically occupy the extreme (highest) temperatures within the landscape, given the maritime influence of temperatures in New Zealand. This is true in the case study area of Western Bay of Plenty and Tauranga. The least invasible area therefore, on the basis of extreme optimums, was upland intact sites which were as far removed from urban areas and with lowest road densities as possible, and the lowest minimum temperatures (July-August). It is expected that since many introduced and cultivated ornamental plants are similarly associated with urban and road disturbance, lowland temperatures (extreme highs) and some with riparian/streams sides, that there will be other species, that have a similar habit to

Tradescantia or occur a similar ecological niche, that can be modelled using the ENFA Extreme optimum medians algorithm.

6. ***In order to track climate and land use change, at the landscape level, Tradescantia will need to migrate in an 'inland and upland direction'. This goes in the opposite direction to natural dispersal which would be mainly in a downstream to lowland direction in the landscape (unless assisted by humans).***

The likelihood of 'inland-upland' dispersal and migration happening by water-aided dispersal alone is, less likely, give that the majority of the infestations are downstream (in the 'core' areas). However, *Tradescantia* has several observed presences (populations) in upland higher elevation sites (in the Kaimai ranges), which are source populations for viable propagules that have the potential to disperse downstream into sites that become more suitable with climate change and land use change, particularly in restored riparian woody areas, under all future combined scenarios of climate change and land use change. These 'upland' infestations provide an advantage to *Tradescantia*, as the species is better poised to take advantage of new suitable sites, by downstream dispersal, which it may have taken a longer time to disperse to in an upstream direction (without aided dispersal, by humans, cattle et cetera). These upstream infestations therefore, pose an extra risk to the invasibility of the landscape under future conditions, and under present conditions to the habitats they are invading. The level of impact is of course a function of the density and abundance of the species and the area covered, and so may not pose an equal risk at all sites. At the landscape level, as Opdam and Wascher (2004) indicates, it is expected that the spatial distribution in fragmented landscapes takes on a metapopulation structure and that future combined scenarios of climate change and land use change will be determined by the factors which consequently control the metapopulation dynamics within the fragmented landscape (which are influenced by the land use and climate changes also). This means that the final structure of the metapopulation (of group of fragmented populations) at the landscape level will be dependent on the physical structure of the landscape in terms of the various land uses and land cover types, and also more detailed and localised factors which determine the colonisation, growth survival and extinction dynamics of local populations. This meta-population level of analysis was beyond the scope and purpose of the present study, however, its value for understanding its likely influence on landscape dynamics must be acknowledged.

7.4 Significance of the research and implications for biosecurity

This is the first time that the combined effects of climate change and land use changes effects have been assessed for an invasive species in New Zealand. The results are relevant to resource managers in the biodiversity and biosecurity fields in particular, at both the national scale and at the regional to sub-regional level of the Western Bay of Plenty and Tauranga. This research, the assessment methodology and results are important to New Zealand in that for the first time, spatially-explicit information on projected climate changes and land use changes are tested within a species distribution modelling exercise.

This assessment also provides a basis from which to expand to assessments of other invasive species (both existing and emerging pests) and to testing in new regions and landscapes within New Zealand and beyond, where appropriate data sets are available. It is particularly useful in applications where what is being tested is the combination of specific climate change scenarios for variables that the invasives species is sensitive to, with scenarios of specific and plausible land use changes, that can be represented for suitable habitats and disturbance sources. This can be done on the basis of projected biodiversity targets or land management measures and urban changes that will changes the spatial extent and configuration of invasibility under future scenarios. Assessments of this sort, for multiple invasive plant species (both existing and emerging) will be essential to get a better understanding of the projected future risks and the spatial shifts projected for various individual species or suite of functional groups of invasive species et cetera. Such multi-species assessments will allow more comprehensive national and landscape level comparisons and assessments of composite risk (sum of species risks). It will also allow another important type of analysis to be done – relative risk analysis (see Figure 7.2) – whereby different landscapes in New Zealand can be assessed using similar methods to assess their relative invisibilities under current and future scenarios of change.

Assessment methods like the one used in this study can be very useful decision-support tools in managing for biodiversity restoration and in assessing how to increase the resilience at the landscape level on the basis of spatially-explicit information that can be used in planning for biodiversity protection and enhancement. Widespread loss of lowland indigenous biodiversity is a national concern for New Zealand (MfE, 2000). As shown in Figure 7.2, most lowland and modified landscapes in coastal regions of New Zealand are acutely or chronically threatened or at risk, with upland areas being typically under protected, at risk or critically under-protected. Only in areas with large tracts of intact indigenous forests, is there no threat category. The case study area for this study represents a complex of acutely threatened lowlands and under-protected uplands. This represents the current situation.

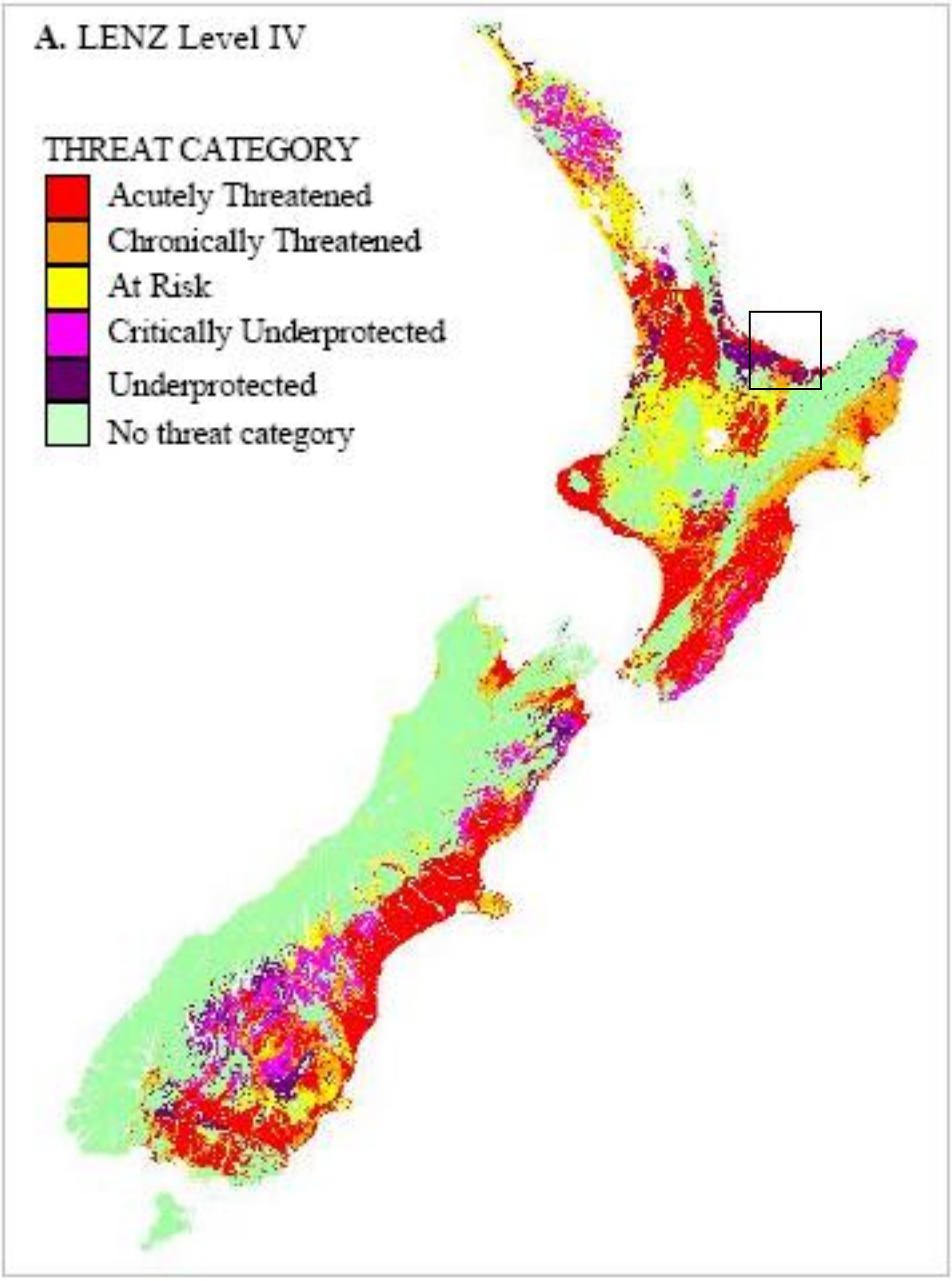


Figure 7.2 The Land Environments New Zealand (LENZ) Level IV Environments showing the various biodiversity threat categories at the national scale. The striking observation is that most lowland areas associated with human settlements are highly modified and as a result are acutely threatened. The window indicates the case study area. (Source: Walker et al., 2008, pg. 23, used by permission).

The ENFA analysis is able to provide specific insight into which habitats under the baseline situation contribute the most to the ecological niche breadth of a species, in other words which habitats it will invade the best, or which habitats are most at risk. On this basis, this study points to some important management implications for riparian woody vegetation, particularly in middle elevation areas to lowland being an effective source-sink habitat as well as a habitat-dispersal-disturbance corridor, at the landscape level. Proximity to urban, proximity to roads and to a much lesser extent the frequency of riparian woody vegetation, contributed largely to the species marginality at the landscape level, in addition to MTminJ-A. Given that the extrapolation models developed at the landscape level are all based on the assumption that the explanatory variables have the same contributions in explaining the future combined scenarios, it follows then that land use change will have a more dominant effect than climate change on the distribution of *Tradescantia* at the landscape level. Additionally, given that MTminJ-A and proximity to urban are quite highly correlated, and it is clearly known that *Tradescantia* is linked with urban areas, it is more likely that at the landscape level, proximity to urban is more the causal variable than MTminJ-A (although it can also be said that MTminJ-A and annual mean temperature are casual factors in more urban settlements in lowland milder climatic conditions.

Urban areas will continue to be the primary receiving environments for *Tradescantia*, under all tested scenarios of climate and land use changes. This means that with the direction of natural dispersal in a downstream fashion and with urban disturbance likely to disperse propagules also primarily into urban environments, these areas will potentially increase in the number of invasions. This is dependent on the level of control also.

In a future that is likely to see more remnant vegetation being linked up through corridors, it will be important for resource managers to incorporate aspects if landscape ecology into their risk and management approaches in order to reflect the fact that re-invasion potential is likely to increase into the future when suitable habitats increase when in conjunction with effective upland source populations and dispersal corridors. Riparian replanting has the effect of increasing the longitudinal habitat continuum and reducing the spread limiting effects of fragmentation on the landscape. Land use changes which increase the amount of suitable habitat available for *Tradescantia* to invade, increase the vulnerability of the landscape to invasion. This is particularly likely to be true of landscapes that are actively being re-planted / re-vegetated to meet various biodiversity, soil and water conservation and land management objectives and targets at the regional, district and city scales. New vegetation that is <9ha in area in terms of patch size, or that is fully edge-dominated habitat, being 50m or less in width, will effective increase the area of suitable habitat. On this basis, new riparian plantings will be especially vulnerable, particularly if there are neighbouring source populations upstream which can provide invasive propagules for the new suitable sites. In the Western Bay of Plenty and Tauranga case study areas, there are multiple upland infestations of *Tradescantia* which will be able to provide downstream new habitats with invasive propagules, particularly if they are riparian infestations: due to the dispersal-disturbance-habitat corridor effect. These landscape-level considerations need to be considered in assessing the risk of an invasive species and the risk posed to new areas of biodiversity or native vegetation from existing and emerging invasive plant populations. The same may also be said about mammalian pests and provision of corridors; however, this is outside of the purview of this study.

From the point of view of protecting large cores areas, this is then an ideal combination, for maximising landscape-level resilience to weed invasion. However, with the increase of suitable habitat corridors into the future with the re-planting work that is going on it will mean that there is likely to be more invasion of suitable sites, give that the priority for new vegetation is riparian which as we know is one of the most suitable sites for *Tradescantia* and also provides natural dispersal for this species. *Tradescantia* maximal suitability is at the extreme on each environmental gradient used in the analysis. Propagule and dispersal limitation for expanding further into newly suitable optimum sites under climate change and land use change will determine the tracking ability of *Tradescantia* to keep pace with climate change and land use change at the landscape scale. At this scale, therefore, the metapopulation dynamics between source and sink population scattered within a patch landscape will need to be assessed. A metapopulation perspective of disjunct populations at the landscape level will incorporate spatial configuration in understanding the colonisation, extinction and dispersal rates of *Tradescantia* that will eventually lead to its long-run environmental persistence in the landscape (Elith et al., 2006 Arau´jo and Williams 2000, Ferrier et al. 2002a, Scotts and Drielsma 2003).

While the sub-regional biodiversity restoration activities through proposed new vegetation additions is greatly needed, and a welcome step in terms of biodiversity restoration in the area, this study shows that some vegetation additions, in particular the woody riparian vegetation, has the potential to put at risk the landscape, given that there are extant source population of multiple invasive species in this landscape, given its current subtropical conditions and climatic suitability. Therefore, the issue of habitat or landscape connectivity which is promoted for the sake of connecting indigenous vegetation and to allow native species to disperse is also effective in allowing invasive species to disperse. This study shows that, it will be important to look at these future changes both from a biodiversity point of view and a biosecurity point of view. In other words, future landscape management in the sub-region calls for twinning biodiversity and biosecurity ecology in landscape and protected area management.

The upland source populations of *Tradescantia* need to be further verified. It would be recommended that as a feasible control measure, those upland source populations which mark ‘starting’ populations along a stream reach (i.e. there are no other source population upstream from it along that stream or river) be eradicated as a first priority, and to progressively remove source populations along streams of rivers that have the potential to invade or re-invade protected areas downstream. This has implications most likely for the Department of Conservation as several upland observations are in DoC administered reserves. In addition where these upland source populations are on private land, owners/occupiers could be asked to remove it as a priority. This will have immediate benefits for the Department of Conservations sites which are also the high priority sites for protection from a biodiversity conservation point of view. In this way it is likely to maximise the biodiversity benefit from the biosecurity effort, which would seem to be a good rationale for taking such control measures.

There is also a need for more strategic planning of riparian planting, in particular, such that upland, upper catchment stream banks which have the least likelihood of upstream source populations of *Tradescantia* providing propagule for invasion and re-invasion of the newly planted sites into the future are replanted as a priority, from a conservation gains point of view. Given that riparian banks need to be re-planted for soil and water conservation there the trend to replant wherever landowners are willing (which has tended to be further downstream) will continue. However, prioritization of re-planting sites in upland hill country areas will necessarily need to take into account the results of multi-species invasive assessments, given that *Tradescantia* is not the only species that is invading habitats. It is important to also look for sites where there is the lowest 're-invasion' potential from upstream sites (of species which are persistent, high impact and which can be dispersed by water).

7.5 Conclusions of this thesis

Using scenarios in this integrated assessment within a species distribution modelling context, is a very useful combination of techniques that provides information useful for decision-makers to explore often uncontrollable, irreducible uncertainty about the future. It offers resource managers, especially at the landscape level, a method for developing more resilient conservation strategies which integrate key climate change, land use changes, invasive species ecology and landscape ecological linkages. The primary objective of using the scenario-based approach was to be able to consider several possible futures that include the key uncertainties in the system for *Tradescantia*'s spatial distribution and spread, rather than to focus on an accurate prediction of a single outcome (Peterson et al., 2003). The scenarios were effective, especially at the landscape level because they focused on the particular issue of invasibility.

One of the key aspects of the integrated assessment was to identify which uncertainties were likely to have a large impact on invasibility. In this case the major uncertainties were linked with climate change and this was the reason why three separate scenarios (CCSR:B1-low, Darlam:A1B-Mid and HadCM:A1FI-High scenarios of climate change) were tested: as one measure to explore the uncertainties associated with climate change. Since only MTminJ-A was tested at the landscape level; this represents only a subset of the possible climate changes and associated uncertainties. However, for *Tradescantia* it was one of the most plausible variables to test. With respect to land use change, the key uncertainties of interest were, by what amount and to what spatial extent urban development will proceed and how vegetation or suitable habitats would change. Since this case study area had 50-year urban development projections tied with migration plausible projections and an environmental enhancement programme that provided specific projection of certain planned vegetation changes in the subregion, this also reduced the uncertainty associated with the land use change scenarios.

The assessment also has relevance for expanding the assessment of effects of urban form on indigenous urban and landscape ecology in the SmartGrowth sub-region, in the light of changing risks associated with climate change, land use change and invasive species (existing and emerging) to regional resource management. The current planning purview does not make explicit mention of invasive species in the ecological assessment of future development. There are also the effects of climate and land use change directly on indigenous biodiversity. A more comprehensive assessment process that it multi-species and incorporates both biodiversity and biosecurity along with the major drivers and pressures of change will be useful for regional resource planning and management over the long run. A scenario-based approach is useful in exploring this process and to identify alternatives for climate change adaptation and land use change management, to improve conservation, environmental enhancement and planned development into the future. As a result the initial scenarios tested could lead to resource managers wanting to test other alternative scenarios to see if the reduce selected risks which are deemed as unacceptable or which the region would like to avoid, for instance. Peterson et al., 2003 conclude that at least 3-4 scenarios must be tested in an assessment, as less that this would limit the ability to expand their thinking around alternatives, and more than this could confuse users and limit their ability to explore uncertainties.

The scenarios-based approach can be used to test, analyse and create policy, in this case related to biosecurity and biodiversity and spatial planning for instance. One policy that stands out as being likely to increase the landscape level vulnerability is the 100% replanting of riparian areas, give the linkages it has as a source-sink habitat and as a disturbance-dispersal-habitat corridor for invasive species. This may be a strong policy from a soil water conservation point of view and as a biodiversity corridor for indigenous species; however it needs to be assessed whether long-term biosecurity-related threats will not undermine some of the anticipated benefits, in landscapes which have multiple source population upstream of highly invasive and high impacts invasive species. This is an area that needs to be explored further.

This integrated methodology is one step towards a better integrated model for conducting sensitivity analysis under the influence of climate and land use change scenarios and has the advantage of including landscape-level invasibility factors that fine-tune the species distribution modelling by being proxies, for mechanistic dispersal-disturbance which facilitates long-distance dispersal and hence range expansion *Tradescantia*'s distribution in New Zealand. These proximate landscape-level factors add more realism to the distribution modelling, given that they relate to the observed mode of spread at the landscape-level. The structure of the models allows for additional datasets (or scenarios) to fine-tune the species distribution, in order to ask 'what if' questions. Both models allow for further development to improve the accuracy of the species distribution and to test different species as well, give that the only dataset that would change would be the 'presence-only' species distribution per species – i.e. all other layers input onto the system are generic to the landscape climate of land use and could be used to assess and contrast impacts across a wide range of plant species in order to assess multi-species impacts in a spatially-explicit way.

There were some clear policy-relevant issues and practical implications that arise from this research that were discussed in Section 7.4. In summary of that discussion **it is recommended that:**

1. land use changes need to be integrated with climate changes in future assessments of effects of the species distributions of invasive species, particularly at landscape to regional levels.
2. ENFA is a suitable and versatile species distribution modelling approach that is able to serve as a useful platform/framework for integrating climatic and land use change effects on species distribution modelling into the future and should be explored for other species.
3. upstream source populations of *Tradescantia*, particularly in proximity to or in areas of high conservation priority need to be controlled or eradicated as an

effective means of reducing propagule sources to downstream infestations, at a landscape level, in regions with significant amount of riparian habitat at present or projected into the future, with restoration efforts.

Feedback from biosecurity practitioners about species distribution and integrated assessment of impacts including:

1) The need for **probability-based** model outputs, which allowed users to assess management-options/choices or priorities with the probability of risk and change to risk within future species distribution scenarios.
2) Capacity for assessing the **costs and benefits** of adaptation/no adaptation are needed
3) Integrated assessment modelling is seen as too complicated by some biosecurity practitioners. This may have the effect of discouraging some potential users and may require re-thinking of how both the methodology and the species distribution outputs are communicated and to whom they are primarily targeted/useful.
4) The species' selected for undertaking integrated assessment need to be of regional priority to the potential users (if a landscape-level assessment), or users will not be convinced of the need for the assessment, particularly if from a pest management point of view, it is a species that is so widespread regionally, that it is not (and will not under current management priorities) be managed to any further degree.

7.5.1 Limitations of the Research

There are a few limitations that are identified with this study which include the following:

1. The integrated assessment focused on a single species only, while biosecurity managers may need to assess the species distribution at the national and landscape level, in the light of similar assessments on other existing or

emerging pests (of multiple taxa) in order to prioritise decisions-making into the future.

2. One potential limitation that may exist is that the realised distribution of *Tradescantia* in New Zealand underestimates to a certain degree the potential distribution. A useful method to avoid underestimating the realised niche is to develop the ecological niche model based on the native range first, and subsequently apply this ecological niche model to the introduced area (in this case New Zealand) to model the realised niche in that area. Since the number of presence records for the native range of *Tradescantia* (i.e., for South East Brazil, Argentina, Uruguay and Paraguay), was insufficient to run an Ecological Niche Factor Analysis on the native range, this step could not be adopted prior to modelling the realised range of *Tradescantia* in New Zealand. The reason why doing this would have been important is to verify whether *Tradescantia* occupies the same/or similar ecological niche (based on climatic factors for example) as in the native range. This is a very important verification, because the whole premise of ecological niche modelling is that the ecological niche of a species will be preserved spatially and temporally, though the geographic range may change in order to fill all areas which represent that ecological niche. This is the underlying rationale for extrapolating the baseline ecological niche to the future in using the climate change and land use change scenarios. Even though the ecological niche could not be developed for the native range of *Tradescantia*, in this project, it is expected that realised range that was produced by the ENFA in New Zealand analysis, does provided a very plausible distribution pattern. It is also likely that New Zealand represents the southernmost border of the global realised range for *Tradescantia* (based on the distribution information available to date in published literature, see Chapter 2).
3. Since species distribution models of many species are likely to be based on the realised rather than the fundamental species niche, projections into future climate, where biotic interactions may have changed (e.g. because of different migration rates), can generate mistakes (Davis et al. 1998). The degree of prediction errors should be related in some way to a species capacity to

> occupy its full fundamental niche in the current and future climate. For most species, it is unknown how much its fundamental niche is represented by its realized niche, although we expect it should relate to its competitive and dispersal abilities. In principle, the same limitation exists when projecting SDMs to other areas with different floras or faunas, testing the transferability of models in space may already provide a useful assessment on the validity of these future projections. This is one reason why *Tradescantia* was chosen as a case study species, because in a global-scale New Zealand is likely to be the southern extreme of this species' distribution, and within New Zealand the species had spread so widely that it is expected that the current *realised distribution* represents the *fundamental distribution* to a large extent, which is important when projecting the distribution into the future with climate change. Additionally, the dispersal ability of this species is high, given that it can be carried long distances both by water and people (though people may transport it less given that it is now against the law to do so, being a National Plant Pest Accord listed species).

An alternative approach would be to base predictive models on fundamental (i.e. physiological) responses obtained from field or laboratory experiments, and constrain these by general rules of biotic interactions, dispersal behaviour and populations dynamics, in order to obtain more realistic predictions of species distribution under changing environments. This fundamental-constrained approach is supported – but also complicated – by the fact that most species seem to be generalists rather than specialists (Huntley et al. 1997), and thus most species are involved in generalist interactions with a large number of other species in any given ecosystem (especially the case with most invasive weed species). In addition, and as a direct consequence of the individualistic behaviour of species, the effects of interacting species in one locality are supplanted by the effects of other species as an assemblage changes across the focal species geographical range (Huntley et al. 2004). Furthermore, a legitimate question is whether such fundamental knowledge will ever be available for many species in the wild. Thus, other alternatives should also be explored and the robustness of current SDMs should be properly assessed, whenever possible, to provide as realistic estimates of climate change impact as possible.

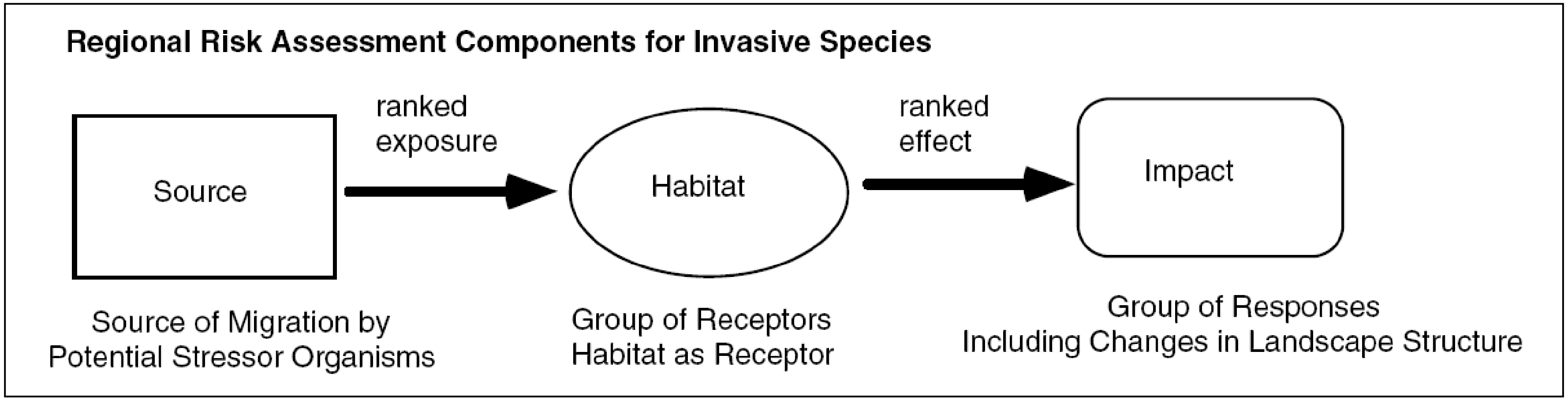
7.5.2 Future Research Suggestions

The assessment methodology used in this thesis has the potential to be extended to a wide selection of invasive species and to be used to collate multi-species data. This has the potential to produce ‘composite’ or aggregate spatial risk mapping capabilities based on climatic and non-climatic data, integrating climate change and land use change scenarios also. Just the baseline modelling and spatially explicit mapping for the invasive species in New Zealand would be a very useful exercise, as the Department of Conservation has identified that the baseline distribution maps are not available for most species. Attempting to do such an exercise will allows species to be screened for instance as follows:

1. which species have sufficient and reliable ‘presence-only’ data within which to undertake and ENFA type integrated assessment using ENFA. Species that would be of interest for such assessment would include other perennial species like: *Vinca major* (Periwinkle), *Hedychium flavescens* (Yellow ginger), *Ageratina riparia* (Mistflower);
2. which species will need to be verified further or missing data checked for data quality et cetera;
3. separating species into: (1) ‘exiting’ weeds and (2) ‘emerging’ weeds, using the classic ‘invasion curve’ used by biosecurity practitioners in New Zealand in the Regional Pest Management Strategies (RPMSs) of regions;
4. Undertaking an adaptation assessment to reduce risk, using such methods as the Climate Change Assessment for Integrated Risk Reduction (CCAIRR) (IPCC, 2007a); and
5. Undertaking economic and social costs-benefit analyses on the various adaptation measures for assess feasibility of implementation.

As mentioned under the national scale assessment of effects of climate change on the distribution of *Tradescantia*, it will be insightful to undertake further analysis to analyse the effects of climate change and land use change on extreme events such as (1) projected changes to frost risk; and (2) projected changes to flood-related disturbance events. It would be useful to explore how this could be integrated with scenarios of land use change, climate change and metapopulation dynamics at the landscape level, in the most sensitive regions, for instance. Some of the other landscapes in New Zealand that warrant the same landscape level analyses where future urban development planning has been done including the following in particular: Nelson/Tasman region, Wellington region, Christchurch and Banks Peninsula and the Kaikoura Coast, and West Coast.

It would also be useful to build a species specific metapopulation model for *Tradescantia* for the case study landscape and for other landscapes as well. Some of the aspects that would need to be fed into a metapopulation modelling exercise are provided in Figure 7.3 (Source of the upper box: Landis, 2004 – relative risk ranking at the landscape level with non-indigenous invasive species) and relate to many of considerations that were made for the landscape scale modelling approach in this study as well and so build on them. Looking at the landscape from this point of view, this study provides the realised and projected scenarios of future distribution of *Tradescantia*, and a metapopulation study would be able to provide more spatial information on the dynamic population-level changes that allow *Tradescantia* to fill the potential habitats that are suitable under the various scenarios (Opdam and Wascher, 2004). In other words, it would provide insight into how *Tradescantia* would potentially spread into the potentially suitable range and will help us to understand better whether the species will be able to track the climate and land use changes into the future. This analysis is likely to be most reliable on the baseline model.



Source	Habitat (Sources and Sinks)	Impact
* Urban gardens * Sub-urban gardens * Rural gardens * Horticultural orchards * Riparian woody vegetation * Woody non-riparian vegetation * Riparian herbaceous vegetation * Roadside habitats	* Riparian woody vegetation * Woody non-riparian vegetation * Riparian herbaceous vegetation	If relative growth rate (RLR) at a site if taken as a measure of impact then, depending on the size and condition of the habitat patch, the impact (RLR) will vary. At a patch level, there is strong evidence that the primary limiting factor for RLR is 'irradiance level' (Maule et al., 1995). Therefore, if vegetation condition is good (i.e. there is canopy closure for example), and there are low light levels into the patch, it is expected that *Tradescantia*'s RLR will be highest at the edge and decrease into the patch for larger patches, >9ha; and edge-dominated patches have the potential to be invaded from edge to edge at higher RLR (Standish et al., 2004).

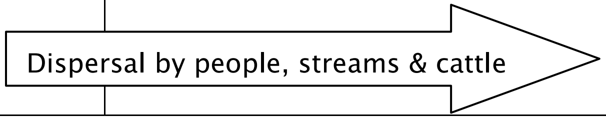


Figure 7.3 A schematic for integrating metapopulation ecology at the landscape level: colonisation, extinction and dispersal can be studied (Top Box, Source: Part B of figure in Landis 2004, pg 849).

7.6 Final reflections

Global change processes including climate and land use change and invasive species, are altering the spatial and temporal dynamics of species distributions in natural and modified systems around the world. The threat this poses to biodiversity conservation is a global environmental concern.

Coupled with these changes, human migration, trade and settlement patterns facilitate large biogeographic shifts from the native ranges of some species, into novel environments, like New Zealand. As a result invasive species present a global scale natural experiment of the changes to the realised distribution range of opportunistic species, often associated with global change processes.

In the past, biodiversity conservation, climate change and land use change (or land management) issues were often dealt with rather independently. Increasingly, the need to integrate various sectors, disciplines and research methods to assess the integrated effects of these global changes has become apparent and needs to be advanced. Indeed to adapting to climate change, it is essential to undertake integrated assessments of vulnerability, impacts and effects, in order to explore the most appropriate environmental, social, economic adaptation measures that can be taken. This study contributed to methods and approaches for assessing the effects of climate and land use changes and invasive species and can be built upon in future work.

It is important for future research to be able to distinguish between effects on ‘existing’ versus ‘emerging’ invasive species, as in the former situation, often very few real alternatives exist, apart from biocontrol for widespread species to be controlled. On the other hand, biosecurity practitioners are hopeful that integrated assessments will allow them to foresee emerging pests which can be eradicated or controlled as an early intervention. However, both types of integrated assessments will continue to be important, as the impacts of both are experienced across ecosystems.

8 Appendix 1: LCDBII Classes

Landcover 2 data set Class	**Generalised Class**
Built-up Area	Urban
Urban Parkland / Open Space	Urban
Surface Mine	Mine or dump
Dump	Mine or dump
Transport Infrastructure	Unclassified
Coastal Sand and Gravel	Coastal Sand
River and Lakeshore Gravel and Rock	River or Unclassified
Landslide	Unclassified
Alpine Gravel and Rock	Alpine Rock
Permanent Snow and Ice	Permanent Snow
Lake and Pond	Lake
River	River
Estuarine Open Water	Sea
Short-rotation Cropland	High Producing Grassland
Vineyard	Horticulture
Orchard and Other Perennial Crops	Horticulture
High Producing Exotic Grassland	High Producing Grassland
Low Producing Grassland	Low Producing Grassland
Tall Tussock Grassland	Tussock
Depleted Grassland	Low Producing Grassland
Herbaceous Freshwater Vegetation	Freshwater wetland
Herbaceous Saline Vegetation	Saltwater wetland
Flaxland	Freshwater wetland
Fernland	Indigenous Scrub

Gorse and Broom	Exotic Scrub
Manuka and or Kanuka	Indigenous Scrub
Matagouri	Indigenous Scrub
Broadleaved Indigenous Hardwoods	Indigenous Scrub
Sub Alpine Shrubland	Sub Alpine Scrub
Mixed Exotic Shrubland	Exotic Scrub
Grey Scrub	Indigenous Scrub
Minor Shelterbelts	Unclassified
Major Shelterbelts	Unclassified
Afforestation (not imaged)	Exotic Forest
Afforestation (imaged, post LCDB 1)	Exotic Forest
Forest - Harvested	Exotic Forest
Pine Forest - Open Canopy	Exotic Forest
Pine Forest - Closed Canopy	Exotic Forest
Other Exotic Forest	Exotic Forest
Deciduous Hardwoods	Exotic Forest
Indigenous Forest	Indigenous Forest
Mangrove	Saltwater wetland

(Source: University of Waikato, Geography Department (2008): http://www.waikato.ac.nz/wfass/subjects/geography/people/lars/landscape/page11.shtml)

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