# Global Change and New Zealand Biosecurity

Nicolas Meurisse (Scion), John Kean (AgR),
Jessica Vereijssen (PFR), Craig Phillips (AgR)

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A word cloud of the most important global issues relevant to biological invasions, summarised from an international survey of 240 experts by Dehnen-Schmutz et al. (2018). The font size of each word or phrase is proportional to the number of respondents who rated it highly.

# Contents

# Executive summary

Crucial New Zealand biosecurity stakeholders, such as the Ministries for Primary Industries, the Environment, Business Innovation and Employment, the Department of Conservation; industry and Māori are rightly concerned about how well border biosecurity systems will perform under future trade patterns, climate change, population mobility, and a range of other global trends.

Better Border Biosecurity (B3) is a 15-year-long collaboration joining these key stakeholders with scientists from Crown Research Institutes, universities, and international experts to provide the science behind protecting our plants from invasive weeds, pests, and pathogens. B3 work is underway in several areas to strengthen New Zealand's borders under current conditions. But the inevitable climate warming, and other impacts related to rapid global change, ignited the collaboration to initiate a project focused on understanding "global megatrends", those most likely to impact on New Zealand's biosecurity system, and recommendations on best response to this inevitable but ultimately unpredictable future.

B3 experts reviewed the many global megatrends that will affect our future, and specifically New Zealand's border biosecurity systems. The drivers are complex and interconnected, and experiences here in New Zealand may differ from elsewhere in the world. Climate change is one of the main megatrends of relevance to border biosecurity, and the review focuses on this while continuing to reference other trends as appropriate.

Direct impacts of climate change will vary across regions, with different crops and sectors being affected differently. Existing crops, such as kiwifruit, citrus, grapes and avocados, will be grown in new areas as local climates change, while new crops may become viable, such as peanuts, soybeans, chickpeas, quinoa, oats, buckwheat, sorghum, pineapple, banana and rice. Other land use changes will also likely favour more forestry and dairy, and reduce sheep and beef production.

Natural environments may be especially vulnerable. However, climate change will interact with land use change and other factors in a dynamic interplay that may be hard to predict. There are many ways border biosecurity will be affected, with current and future crops and landscapes being threatened by new suites of pests, weeds and pathogens that may or may not already be present in New Zealand.

Biological invasions principally result from human factors, strongly associated with long-distance exchanges of traded commodities and international travels. The expansion of agriculture and increased cultivation of ornamental plants have also triggered range expansions into locations where weeds and pests would never have been able to establish before. Under climate change and other agricultural or societal developments, invasion pressure from exotic pests is expected to increase. More frequent and damaging extreme weather events may also increase the movement of pests over long distances and across physical barriers.

This report concludes there is a need for cross-sector and cross-disciplinary research to address the biosecurity implications of global megatrends, including climate change.

The greatest priority is to make the border system robust, resilient and responsive to a wide range of future biosecurity challenges. Examples of achieving this include improving trait-based approaches to risk assessment of future pests and threats, new methods to forecast, track and monitor changing border pressures, and better understanding vulnerabilities of host plants and ecosystems and the potential impacts of invasive pests and pathogens. Another priority addresses evolving technologies and policies, which may affect our modes of operation and ability to perform biosecurity interventions. The report also provides specific recommendations for B3 around inclusion, collaboration, coordination, and data sharing.

# Introduction

Border biosecurity helps to prevent or reduce damage to New Zealand's unique species and ecosystems by preventing the entry and establishment of exotic organisms. New Zealand's regional and national economies depend on primary production and associated trade of agricultural products. Thus, New Zealand is more dependent on biosecurity than many other developed countries.

Due to its biogeographical isolation, New Zealand has native plant and animal communities that are particularly vulnerable to the impacts of biological invasions. Despite the country's insularity and stringent biosecurity system, New Zealand's borders are being challenged by intensifying movements of people, goods, and vessels. In addition, climate change has high potential to disrupt the biosecurity system: the atmosphere and seas are warming at unprecedented rates, extreme weather events are becoming more frequent and more damaging, and significant pest redistributions may occur as global food production and trade are altered by shifting climates and other components of global change.

New Zealand's future land use and agricultural practices will change because of climate change, including the crops we grow and where we grow them. The overseas pests that are the most likely to invade and establish in New Zealand will change, as will the distributions and abundance of pests that are already here. A different suite of biological invaders may find themselves able to establish in New Zealand, while new threats may emerge from the thousands of exotics already present. There will be important consequences for our biosecurity priorities and our ability to prevent future invasions.

Worldwide, irreversible consequences are predicted to affect our natural and agricultural environments, our economy, and ways of life. Some developing impacts are already apparent today. For instance, substantial changes in natural vegetation structure and ecosystem processes are already attributed to anthropogenic climate modifications, such as poleward and altitudinal shifts of natural vegetation systems. Transitions in agricultural systems are also occurring but are generally being driven by changes in supply and demand for food and fibre products. Detecting and attributing the effects of climate change is more difficult in these agro-economic systems. Nonetheless, food provisioning is a key element of global change risk profiling, and it will inevitably be impacted by climate change's cascading effects on global and regional economies, international politics, and human migration.

Here we collated and reviewed current knowledge of how global changes, especially climate change, might impact on plant biosecurity risks in New Zealand. The project initially focused on stakeholder engagement and identifying which global change "megatrends" were of greatest relevance to plant pest invasions in general, and which ones should be a research focus for plant border biosecurity. We worked with the New Zealand government (Ministry for Primary Industries (MPI)), primary industries and other stakeholders to understand the impacts of climate change for primary production, trade and pest pressure. The results from two workshops, alongside results from a survey sent to stakeholders (24 respondents) and other reporting, such as the Intergovernmental

Panel on Climate Change (IPCC) Scientific Review of Impact of Climate Change on Plant Pests, indicate complex relationships between climate change, trade and biological invasion risks.

The project team also curated a library of more than 600 documents, reviewed key publications on climate change and biosecurity, and identified global megatrends with potential biosecurity implications for New Zealand. This report reviews that literature, reports on the workshops and survey, and suggests research priorities for plant biosecurity. We focus on direct and indirect effects of global change on plant pests, weeds and diseases, hereafter referred to as “pests”. We touch only briefly on the ways that pests and diseases help drive global change; that topic arguably deserves its own review.

We begin by summarising the relevant global change mega-trends (section 1). Subsequent sections focus on climate change, and particularly on how New Zealand climatic conditions and land use may change (section 2), how pest species are already spreading globally and new ones may emerge as important threats (section 3), and how the global and local distributions of current and future pests may affect their biosecurity risks and impacts (section 4). Finally, we describe the results of our survey of the New Zealand border biosecurity community (section 5) and discuss general and specific recommendations for further research (section 6).

# Section 1. Global change

## Global change megatrends

What new challenges and opportunities does the future hold? When we consider the future, it is tempting to focus on the topics that are the best known and that have generated the most discussion, such as population growth, climate change and biodiversity loss. However, these are just a few of the global "megatrends" that will shape our future. What is at stake may be our very ability to survive and thrive on a resource-limited planet with inherent boundaries for a safe operating space (Steffen et al., 2015).

Many authors have formulated or reviewed lists of current megatrends (e.g., Slaughter 1993; Day et al. 2014; Hajkowicz et al., 2012; Hajkowicz 2015; Retief et al., 2016; Maggio et al., 2018; Artuso & Guijt, 2020; Hatfield-Dodds et al., 2021). The European Commission provides a "Megatrends Hub" at https://knowledge4policy.ec.europa.eu/foresight/tool/megatrends-hub_en, with linked information, tools and training resources on 14 megatrends:

1. diversifying inequalities;
2. climate change and environmental degradation;
3. increasing significance of migration;
4. growing consumption;
5. aggravating resource scarcity;
6. increasing demographic imbalances;
7. expanding influence of the East and global South;
8. accelerating technological change and hyperconnectivity;
9. the changing nature of work;
10. diversification of education and learning;
11. shifting health challenges;
12. continuing urbanisation;
13. increasing influence of new governing systems; and
14. a changing security paradigm.

Hajkowicz et al. (2012, 2015) propose seven, more general megatrends:

1. increasing demand for limited natural resources ("more from less");
2. a window of opportunity to protect biodiversity, habitats and the global climate ("going, going, gone");
3. rapid economic growth in Asia and the developing world ("the silk highway");
4. an ageing population, changed retirement patterns, chronic illness and rising healthcare expenditure ("forever young");
5. digital technology is reshaping retail and office precincts, city design and function and labour markets ("virtually here");
6. consumer and societal expectations for services, experiences and social interaction ("great expectations"); and

7. technological advancement is accelerating and it’s creating new markets and extinguishing existing ones (“the innovation imperative”).

This multitude of interacting changes makes it impossible to reliably predict the future. While there is general agreement about the nature of current trends, different authors have grouped and generalised them differently to suit their purposes. For example, Hatfield-Dodds et al. (2021) emphasised market, trade, resource and disruption trends as of greatest relevance to Australian agriculture:

1. population and wealth are increasing the number of future consumers of food and fibre (“growth juggernaut”);
2. most of the world’s economy is controlled by just seven blocks with vastly different politics, being USA, EU, China, India, Brazil, Russia, and Indonesia (“fractal politics”);
3. agricultural production increasingly relies on innovation to overcome resource limitations, but benefits are not being shared evenly (“more from less”);
4. accelerating changes in earth systems, including climate change, are creating multiple risks and challenges, but some opportunities (“cascading planetary risks”); and
5. advance in digital technologies, automation, genetics and synthetics will disrupt and change how food and fibre are made, marketed and delivered (“disruptive technologies”).

The Food and Agriculture Organization of the United Nations (FAO, 2017) highlighted a similar list of trends and challenges for the future of food and agriculture. Notably, they listed “transboundary pests and diseases” as one of the trends, and also as one of their ten key challenges for the future.

## Global change and plant biosecurity

We reviewed published descriptions of global megatrends and identified those of greatest direct relevance to biosecurity. Unlike other authors, we tried to avoid generalising. For example, we treated $CO_2$ increase, climate change, climate extremes, sea level rise, sea/air currents, wildfires and erosion separately rather than including them all under “climate change”. This allowed us to consider in more detail how different trends may be interrelated (Figure 1), similar to how Yokohata et al. (2019) focused on the risks associated with climate change and tried to capture and visualise the interconnections between them. Each trend is elaborated in Table 1, with a summary of how they may impact on biosecurity. Not all of the trends we list will strongly affect biological invasions in general and plant biosecurity in particular, but we can be confident of identifying the most influential future changes for plant biosecurity, if not the actual magnitudes of their effects.

The megatrends illustrated in Figure 1 are strongly interrelated, and most can be traced back through the diagram to population growth, industrialisation and urbanisation. The demands of a growing global population (Lutz & Samir, 2010) for food and goods underly current innovations in commerce, biotechnologies and agricultural intensification. But population growth creates issues for land use, built infrastructure, waste management, pollution and public health. An increasingly urban population (Li et al., 2019) may have less appreciation for the critical factors underlying food production and security, such as biosecurity. One of the most pressing trends arising from the demands of an increasingly industrialised global population is climate change.

Climate change, caused largely by increasing atmospheric $CO_2$, will be a pervasive and defining characteristic of the 21st century (IPCC, 2021, 2022a). Free-air $CO_2$ enrichment (FACE) experiments show that the rise in atmospheric $CO_2$ is likely to have direct effects on plant growth and physiology, including increased potential crop yield but reduced nutritional content (Ainsworth & Long, 2021). However, the magnitudes of these effects vary between plant types and interact with local climate (ibid.), itself affected by increasing $CO_2$.

Climate change is leading to shifting weather patterns and changing local conditions. The warming trend is melting polar and alpine ice melt causing sea levels to rise (e.g., Garner et al., 2018), leading to negative impacts of waves, current-induced sediment transport, and extreme storms affecting coastal communities and ecosystems (IPCC, 2022a; Mentaschi et al., 2018; Murray et al., 2019; Oppenheimer, 2019). Another consequence of sea level rise will be a need for new infrastructure including seaports (Hanson & Nicholls, 2020) and airports (Yesudian & Dawson, 2021). Changing rainfall patterns are leading to water shortages in some areas and increasing extremes of flooding and drought in others (e.g., Zhai et al., 2020). Wildfires resulting from hot dry conditions (Krawchuk et al., 2009) modify vegetation patterns over large areas and facilitate dispersal of insects and pathogens by convecting propagules high into the atmosphere (Mims & Mims, 2004). In some regions, significant areas of productive land will be lost to sea level rise and desertification (e.g., Huang et al., 2020). Land that would otherwise supply food may be co-opted instead into producing biofuels (e.g., Rodionova et al., 2017). Growing imbalances in land, water and labour resources may result in resource grabbing (Borras et al., 2011) and increase the probability of international conflict or war (Zhang et al., 2007) and human migration (e.g., Grecequet et al., 2017), both of which may accelerate biological invasions (Australia Quarantine and Inspection Service (AQUIS), 2000).

Climate change and ocean currents are intimately intertwined. Ocean circulations potentially regulate and redistribute increased global mean temperatures (e.g., Winton et al., 2013). Meanwhile, strengthening winds seem to be speeding up ocean currents (Hu et al., 2020). Indeed, interactions between the atmosphere and oceans are a major source of uncertainty in future climate projections (Deser et al., 2012). Increasing strength of air and water currents may facilitate natural spread of invasive species, potentially increasing biosecurity risks to New Zealand from Australia and Africa (e.g., Yen et al., 2014) via pathways that are very difficult to manage.

Increasing nitrogen emissions (Battye et al., 2017) and subsequent nitrogen deposition from the atmosphere to soils (Kanakidou et al., 2016) is changing local biodiversity (Maclean & Wilson, 2011). Due to this and other environmental stressors, widespread biodiversity loss has been reported (e.g., Wagner et al., 2021), which may have catastrophic impacts on some ecosystem services such as pollination (e.g., Rhodes 2018).

Most previous improvements in agricultural productivity have arisen from increased inputs of water and nutrients, but as such resources become scarcer, future food production will rely more on improved efficiencies (Ramankutty et al., 2018). Current methods of agricultural intensification are not sustainable (Struik & Kuyper, 2017). Radical new innovations may be needed, such as robotic agriculture (King, 2017), vertical farming (Benke & Tomkins, 2017) and biomanufacturing (Mitsuishi et al., 2013). The biosecurity implications of these new agricultural systems do not appear to have been considered yet.

Many of these global trends arose, sometimes unexpectedly, from technological advance, and research and technology will certainly be needed to address them. But as they affect us all, so must we explore a diversity of responses that may bring together science, technology and indigenous knowledge.

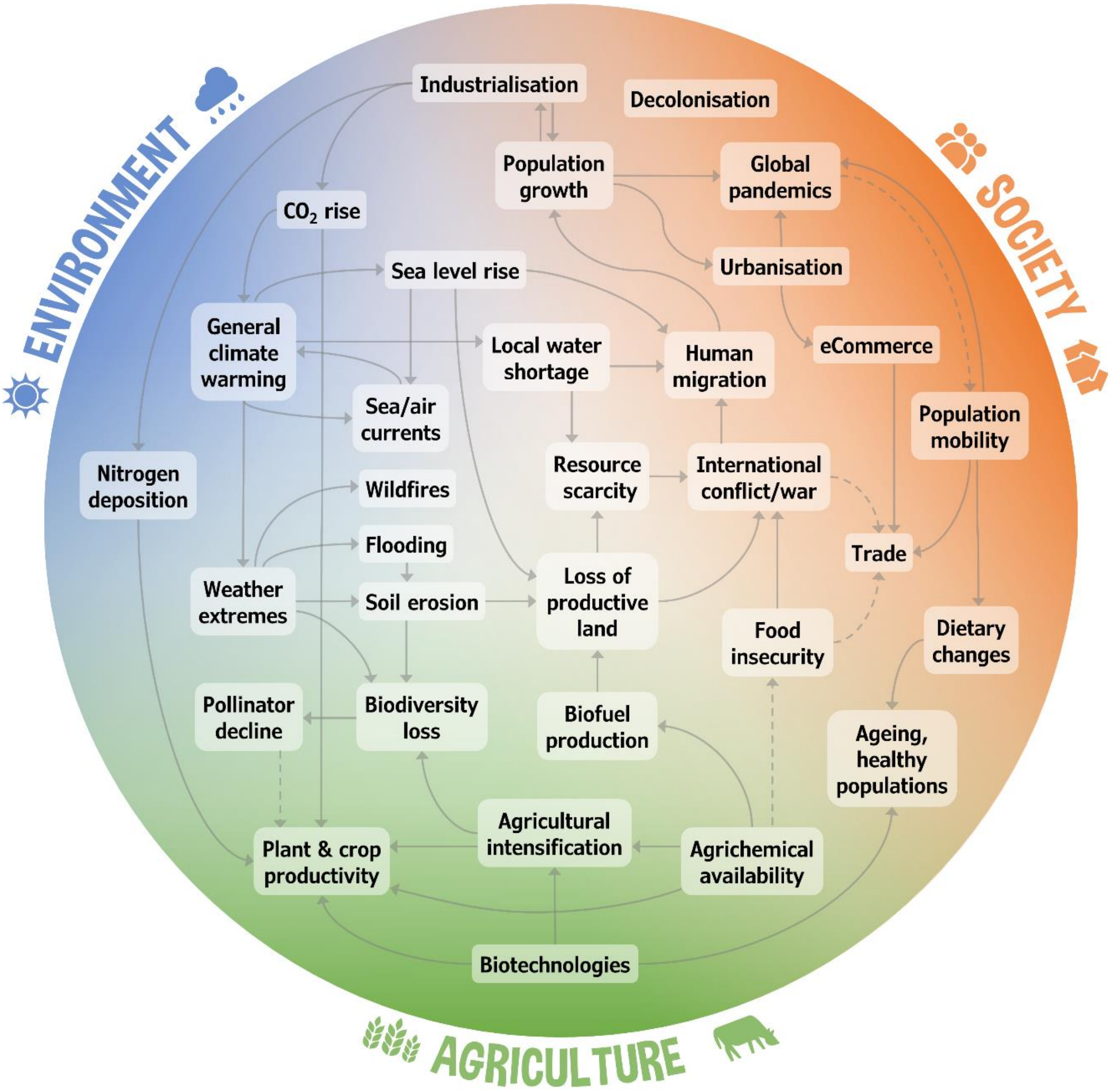

**Figure 1**. Summary of selected aspects of global change, excluding biological invasions, with arrows indicating some of the potential interrelationships between these factors. Solid arrows indicate an expected positive influence, while dashed arrows suggest a negative influence. This non-exhaustive summary shows that there are many expected trends, and these are interconnected.

**Table 1.** Summary of global trends and their relevance to New Zealand and its biosecurity. Global trends are shown in alphabetical order as in Fig. 1. Some of the comments (the ones not cited) come from the writers of this report.

| Global trend | New Zealand situation | Potential biosecurity implications |
|---|---|---|
| **Agrichemical availability.** The demand for chemical pesticides for food production is increasing (Delcour et al., 2015). Existing broad-spectrum pesticides are being withdrawn, and some are being replaced with targeted 'greener' chemistries. | New Zealand's relatively small market makes it uneconomic for pesticide companies to register their new products for use here, meaning there are few or no products to replace the existing broad-spectrum pesticides that are being withdrawn (Goldson et al., 2015). | Loss of agrichemical availability may increase biosecurity risk by allowing pest populations to increase overseas (e.g., Queensland fruit fly increased hugely in Australia after two key chemicals were withdrawn (Reynolds et al., 2017)) and hamper our ability to manage risk at- and post-border (e.g., with methyl bromide). |
| **Agricultural intensification**. Intensification leads to increased food production but does not typically release land for biodiversity preservation (Rudel et al., 2009). The increased value of intensified land makes it difficult to retire for other purposes (Phelps et al., 2013). | Agricultural intensification is ongoing and accelerating, but the biodiversity implications of this have not been well studied (Moller et al., 2008). | Intensified production systems may be more vulnerable to disruption by pests and diseases (e.g., Wilby & Thomas, 2002). Similarly, the potential economic impact of weeds is greatest in high-value production systems. Therefore, intensification relies on effective biosecurity. |
| **Atmospheric pollution**. Air pollutants can cause serious human health issues as well as ecosystem damage, including acid rain. Atmospheric pollution problems tend to be localised (World Air Quality Index (WAQI), 2021). | Air pollution in New Zealand is generally low in comparison to the rest of the world (Kuschel et al., 2022). | Implications for biosecurity may be minor. |
| **Biodiversity loss**. The current global trend in biodiversity loss is both catastrophic and unprecedented (Novacek & Cleland, 2001). | New Zealand has the highest proportion of threatened indigenous species in the world (Ministry for the Environment (MfE) & Stats NZ, 2019). | Alien pests and diseases may threaten already weakened native species. Local extinctions may make niche spaces available for invading species to occupy. |

| Global trend | New Zealand situation | Potential biosecurity implications |
|---|---|---|
| **Biofuel production**. Biofuel crops may put substantial additional pressure on productive lands (e.g., Warner et al., 2013), but microalgae may allow biofuel production (Rodionova et al., 2017) in otherwise barren lands (Correa et al., 2019). | Current biofuel production in NZ uses waste products from other industries (e.g., biodiesel made from tallow, bioethanol from dairy by-products). However, these are tiny amounts compared to the country's energy needs. | New/increased need to protect key biofuel crops from pests and diseases. Large monocultures of biofuel plants may facilitate new establishment of pests and diseases. |
| **Biotechnologies.** The range and scope of biomanufacturing has been steadily growing (Zhang et al., 2017) with advances in chemical and drug manufacture, energy production, waste biomass transformation, mining, and other fields. | In NZ, biotechnologies involving new organisms are subject to approval by the EPA and must be approved on a case-by-case basis with input from Māori and other groups (Hudson et al., 2019). | Biomanufacturing cultures need to be protected from pathogens, though this is generally done by using sterile production areas. Field-based biotechnologies may be more vulnerable to pest and pathogen attack. |
| **Climate change.** Local climates are changing in response to increasing atmospheric $CO_2$, methane, etc. There is a general warming trend (IPCC, 2021). | NZ is expected to get generally warmer, with the west becoming wetter and the east drier (MfE, 2018). Broader implications for NZ are reviewed by Lawrence et al., (2022). More detail is provided in Section 2 of this report. | Pest distributions will shift globally, while NZ crop and pest distributions will also shift (see subsequent sections). There will be many broader implications for biosecurity (Kean et al., 2015; Lawrence et al., 2022). |
| **Climate extremes.** Extremes of temperature and rainfall may become increasingly influential in determining species' geographic ranges (Diez et al., 2012). Intensified weather patterns may lead to flooding, erosion, wildfires and other ecosystem-level impacts (IPCC, 2022a). | NZ's maritime climate is less likely to experience the same extremes as in continental areas. Number of frost days will decrease and number of warm days increase. Extreme rainfall events will increase, and droughts will increase in severity, especially in already dry areas (MfE, 2018). | Climate extremes may disrupt and stress ecosystems, potentially facilitating invasion by species able to establish quickly after disturbances or to adapt to a range of environmental conditions (Lawrence et al., 2022; MfE, 2020a). |

| Global trend | New Zealand situation | Potential biosecurity implications |
|---|---|---|
| **$CO_2$ rise.** Increasing atmospheric $CO_2$ may increase potential crop yield but reduce nutritional content (Ainsworth & Long, 2021). Plant responses to elevated $CO_2$ are complicated by interactions with factors such as drought or warming (Vila et al., 2021). | NZ will be subjected to the same levels of atmospheric $CO_2$ increase as everywhere else. | Increasing $CO_2$ modifies the balance of plant defensive hormones, potentially making them more susceptible to attack (Zavala et al., 2017) or increasing the virulence of plant pathogens and insect pests (Trębicki et al., 2015, 2017). |
| **Decolonisation.** Social and political changes are empowering many indigenous peoples around the world to reconnect with their identity and have greater control over their nation's development. | The number of speakers of te reo Māori was systematically reduced in the colonial period. Language revitalization strategies have been implemented with a target that 1 out of 5 New Zealanders will be able to speak at least basic te reo Māori by 2040 (Te Puni Kōkiri, 2018). The increasing use of te reo Māori is one of the most visible signs of a resurgence in Māori culture, arts, values and representation at all levels of New Zealand governance, society, business and national identity. | Biosecurity risks, actions and impacts need to be evaluated through multiple world views and address more diverse economic, environmental, socio-cultural and te ao Māori values. |

| Global trend | New Zealand situation | Potential biosecurity implications |
|---|---|---|
| **Dietary changes**. Dietary guidelines increasingly reflect sustainability goals (Binns et al., 2021), including prospects for climate change mitigation (IPCC, 2022b). Food diversity is expected to decrease (ibid) despite new food types, such as insects (e.g., Kim et al., 2019). Currently 84% of global calories come from just 17 crops (Ramankutty et al., 2018). Proteins derived from plants, like flaxseed, soy, and pea proteins, are increasingly considered viable alternatives to animal proteins (Langyan et al., 2022). | NZ is experiencing increasing demand for sustainable and healthy food, and unprecedented increases in the prevalence of both malnutrition and noncommunicable diseases (Coad & Pedley, 2020).<br>Identified impacts of developing a plant-based protein industry can be positive (e.g., a potential decrease of greenhouse gases emission and nutrient runoff, new markets for new products) and negative (disruption to the current economics of dairy and meat products) (https://ourlandandwater.nz/news/announcing-20-new-research-projects/). | Production of organic and "spray free" foods may be particularly susceptible to disruption from pests, weeds and pathogens. Protein-producing plants may gain value and become intensively cultivated. Reduced demand for animal proteins may reduce issues associated with invasive pasture grasses used to feed livestock (Driscoll et al., 2014). Reductions in livestock numbers could reduce dispersal of weed seeds or favour invasive weeds that were previously controlled by grazing. |
| **eCommerce**. In 2020, retail e-commerce sales worldwide amounted to 4.28 trillion USD and e-retail revenues are projected to grow to 5.4 trillion USD in 2022 (www.statista.com). | The NZ eCommerce market grew by 20% in 2020 and a further 15% in 2021 (https://ecommercedb.com/en/markets/nz/all). | Internet ordering of overseas goods has resulted in significant changes in the volume and risk of items coming through the mail pathway. |
| **Erosion & desertification.** Erosion rates in agricultural lands are an order of magnitude higher than natural processes (Ramankutty et al., 2018). | 5% of NZ's land is currently classified as highly erodible (MfE & Stats NZ, 2019). | Eroded and stressed landscapes tend to favour early-succession species, of which many are considered weeds or pests. |
| **Flooding.** Both sea level rise and greater extremes in local weather patterns will lead to more frequent coastal and river floods (Paulik et al., 2019). | Climate change is likely to change flood risk for exposed populations and infrastructure by around 20% (Paulik et al., 2019). | Biosecurity implications may be minor. |

| Global trend | New Zealand situation | Potential biosecurity implications |
|---|---|---|
| **Food insecurity.** Climate change impacts on food security will be worst in countries already suffering high levels of hunger and will worsen over time; food inequalities will increase (Wheeler & von Braun, 2013). Climate change mitigation may exacerbate food insecurity (Fujimori et al., 2019). | NZ is not projected to experience significant crop yield losses due to climate change before 2050 (Wheeler & von Braun, 2013). However, pests and diseases continue to threaten and impact on NZ's productive sectors. Agricultural climate change mitigations in NZ, for instance under the ETS & He Waka Eke Noa, also may lead to the replacement of pastoral livestock production with forestry. Limits on nutrient and water use can also affect food production sectors. | Biosecurity is essential for maintaining NZ's primary industries as future threats change. The return on investment for biosecurity activities has been estimated at around 30:1 for Australia (Dodd et al., 2020). |
| **Global pandemics.** The risks of emerging infectious diseases are higher than ever, and apparently accelerating (Jones et al., 2008; Marani et al., 2021). | NZ's effective management of the COVID-19 pandemic relied heavily on border closure and a science-led strategy of elimination (Geoghegan et al., 2021). | The media attention given to pandemics like COVID-19 make the public aware of general biosecurity concepts, but it is not clear how well these concepts carry over to plant pests (S. Finlay-Smits et al., unpublished data). |
| **Health & longevity.** Emerging technologies in medicine, such as gene therapy (e.g., Wang et al., 2018; Li and Huang 2000), stem cell-based therapies (Aly, 2020) and rapid vaccine development (e.g., Black et al., 2020), promise to continue the current trend of longer healthy life expectancy and an ageing population structure (Tinker, 2002). | Since 1953, the life expectancy of New Zealanders has increased from 67 to 80 for males and 71 to 83 for females, projected to increase to 87 for males and 90 for females in 2070 (Stats NZ, 2020a). The Ministry of Health is guided by a Healthy Ageing Strategy that aims to improve the health of older people, into and throughout their later years. | An increasing population of fit and healthy retirees may be a resource for citizen-based biosecurity activities such as general surveillance (Kruger et al., 2020) and control (Lewis & Popay, 2006). |

| Global trend | New Zealand situation | Potential biosecurity implications |
|---|---|---|
| **Industrialisation.** De-industrialization was widespread until the early 2000s, but then the global trend reversed due to increasing industrialisation of developing Asia and sub-Saharan Africa (Kruse et al., 2021). | Up to 1998, NZ's primary sector was growing faster than its secondary (industrial) sector (Easton, 1998). That trend has continued, with the share of the economy contributed by primary industries increasing while that of goods-producing industries has declined (Stats NZ, 2020b). | Industrialisation may result in shifts in the sources of imported goods, potentially exposing importing countries to new suites of biosecurity threats. |
| **International conflict/war**. Causal links have been substantiated between food security and violent conflict at all scales (Martin-Shields & Stojetz, 2019). For example, the current Ukraine war has had significant impacts on international food and energy supplies. A recent rise in authoritarian leadership may arguably increase the incidence of international conflict. | NZ's small size and geographic isolation may mean it is unlikely to be directly contested. However, NZ troops have been active in various wars around the globe. | Military vehicles and equipment are well documented as being responsible for biological invasions (e.g., Rodda et al., 1992; Kiritani & Yamamura, 2003). The same has been shown for post-natural disaster relief interventions (e.g., van den Burg et al., 2020). Normal border protection measures may not be feasible under international conflict or other emergency situations. |
| **Loss of productive land.** Some of the increase in global production has been due to cropland expansion (Ramankutty et al., 2018), but meanwhile productive land is being lost to erosion, salinisation and urban sprawl. | Urban spread in NZ is differentially locking up the best soil resources (MfE & Stats NZ, 2021; Rutledge et al., 2017). | Crops and croplands may become increasingly valuable, increasing the real costs of crop damage due to pests, pathogens and weeds. |

| Global trend | New Zealand situation | Potential biosecurity implications |
|---|---|---|
| **Migration.** Currently, almost half of international migrants come from Asia; South America, Africa and Asia are net sources of migrants, while North America, Europe and Oceania are net recipients of migrants (Vidal & Dag Tjaden, 2018). Future climate, ecological and geopolitical trends may trigger increased human migration to less vulnerable areas (Grecequet et al., 2017). | The number of NZ residents who were born elsewhere has doubled since 1990 and comprises 22% of the population; the vast majority of these are from the UK, followed by China, India, Australia and South Africa (United Nations Department of Economic and Social Affairs (UN DESA), 2019a). NZ may be too remote to feel significant effects of forced human migration, except from the Pacific and Asia. However, NZ may be compelled to welcome more 'climate refugees' on compassionate grounds. | New immigrants may preferentially import from or visit their source country, affecting pathways of pest entry. Migrants may be less aware of, or less engaged in, border biosecurity practices. |
| **Nitrogen deposition.** Increasing nitrogen emissions (Battye et al., 2017) and subsequent nitrogen deposition into soils (Kanakidou et al., 2016) is affecting local biodiversity (Maclean & Wilson, 2011). Meanwhile, manufacturing of nitrogen fertilisers has a high carbon footprint (Hillier et al., 2009). | Industrial emissions of nitrogen are minor in NZ. However, much of NZ's pastoral agriculture production increasingly relies on application of nitrogen fertiliser (MfE & Stats NZ, 2021), which has a high carbon footprint. In 2016, nitrogen fertilisers were responsible for 5.7% of NZ's agricultural greenhouse gas emissions (Gibbs, 2019). | As nitrogen fertilisers becomes more expensive, the value of nitrogen-fixing plants (e.g., legumes) and their associated rhizobia is increasing. B3 and DairyNZ have identified many border biosecurity risks to forage legumes. |
| **Plant & crop productivity**. Recent increases in crop productivity resulted from increased inputs of water and nutrients, but future improvements will come more through input efficiency (e.g., precision agriculture) (Ramankutty et al., 2018). | NZ's agricultural and horticultural production has continued to increase, year on year, due to ongoing improvements in management, genetics, inputs and labour productivity (i.e., automation) (Robertson, 2010). | High value production systems may suffer greater costs of damages from pests, weeds and diseases. |

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|---|---|---|
| **Population mobility**. From 1990 to 2019, annual air passengers more than quadrupled (https://data.worldbank.org/indicator/IS.AIR.PSGR) | Prior to the COVID-19 pandemic, most visitors to NZ came from Australia (39%), China (11%), USA (9%), and UK (7%)(Stats NZ, 2018). Total tourist arrivals had been trending upwards to almost 4 million annually, with particularly rapid increases in cruise passengers. | Travellers to NZ are a major pathway for introductions of unwanted organisms, especially "hitchhiker" species which are difficult to predict and manage. |
| **Pollinator decline**. There is mounting evidence that populations of pollinating insects are declining globally (Rhodes, 2018). | NZ bee populations were recently hit by introduction of the Varroa parasite. | Increased urgency to exclude pests (including predators) and diseases of pollinators (e.g., bees). |
| **Population growth**. The current world population of 8 B is expected to increase to 9-11 B by 2100 (UN DESA, 2019b). The proportion of elderly people will increase significantly. | NZ's population is expected to increase from 5.1 M to around 7 M by 2073, with the proportion aged 65+ increasing from 16% to 30% (Stats NZ, 2020). | Burgeoning populations will put increasing pressure on border biosecurity and plant ecosystems, increasing the significance of biosecurity threats. |
| **Resource scarcity.** To date, technological progress has mitigated natural resources scarcity, this is unlikely to continue indefinitely (Krautkraemer, 2005). | NZ's economy depends on imports of locally scarce resources, such as crude oil, phosphate, urea, machinery, and labour. | Trade is driven in part by scarcity, so scarcity may influence biosecurity risk. Maintaining crop yields with reduced fertiliser inputs may necessitate improvements to pest management and border biosecurity. |
| **Sea/air currents**. Strengthening winds are speeding up ocean currents (Hu et al., 2020). | The El Niño-Southern Oscillation (ENSO) is predicted to remain the dominant mode of natural climate variability in the 21st century. NIWA projects stronger westerly weather patterns across the Tasman Sea, especially in winter, and especially affecting the lower North Island and South Island (MfE, 2018). | Increasing risks of natural dispersal by wind and rafting. These pathways are difficult to manage. |

| Global trend | New Zealand situation | Potential biosecurity implications |
|---|---|---|
| **Sea level rise.** Due to ice melting, by 2100 sea levels are expected to rise by 50-130 cm (Oppenheimer & Alley, 2016). Currently 230 million people worldwide are estimated to live less than 100 cm above current sea level (Kulp & Strauss, 2019). | Two thirds of New Zealanders live within 5 km of the coast. By 2050, coastal ingress is projected to affect substantial areas of Kaipara Harbour, Otaua, Hauraki Plains, Te Puke, Edgecumbe, Poverty Bay, Napier, Foxton, Lake Wairarapa, Blenheim, Westport, Kaiapoi, Christchurch, Lake Ellesmere, Taieri Plain, Paretai, Invercargill/Awarua, and Haast (https://coastal.climatecentral.org/map). | With increasing coastal erosion, the value of plants that stabilise coastlines, estuaries and dune systems will be greater. |
| **Trade.** Since the mid 1900's global trade has more than doubled every 20 years (https://ourworldindata.org/trade-and-globalization). New trade routes include the Arctic Ocean and the Suez and Panama canals. Regional effects of climate change are expected to alter patterns of supply and demand, resulting in shifts in trade routes (Kompas et al., 2018). | The model of Kompas et al. (2018) is being refined to examine the likely future shifts in trade routes to NZ (SLMACC funded project to Scion). In 2020, the biggest source of imported goods into NZ (by value) was China (23%), followed by Australia (12%), USA (10%), Japan (6%) and Korea (5%) (Stats NZ, 2022). Imports from Asia, especially China, comprise an increasing proportion of the total. | Increase in global trade is expected to accelerate biological invasions (Seebens et al., 2021). Shifts in the origins of trade may expose NZ to new suites of biosecurity threats. |
| **Urbanisation**. In 2007, half of the world's population was urban. This is expected to exceed two thirds by 2050 (Li et al., 2019; UN DESA, 2019c). | In NZ, 86% of people currently lives in urban areas, though many work in rural occupations. | Urban populations may be less aware of risks associated with pests and diseases. Most new incursions in NZ occur in urban areas, where obtaining social licence to respond may be most problematic. |
| **Waste**. Globally, humans currently generate 7-10 B tonnes pa of urban wastes, with waste generation strongly correlated with national | NZers each generate, on average, 3,200 kg of waste each year, of which only 28% is recycled (recycle.co.nz). | Biowaste and municipal compost can facilitate spread of plant pests, particularly pathogens (Pietsch, 2005), and rubbish dumps have been |

| Global trend | New Zealand situation | Potential biosecurity implications |
|---|---|---|
| income (United Nations Environment Programme (UN EP), 2015). | | recognised as “invasive plant epicentres” (Plaza et al., 2018). |
| **Water shortage**. Agricultural production accounts for 92% of human water use (Ramankutty et al., 2018). Global demand for water, and abstraction of non-renewable groundwater are increasing (Wada & Bierkens, 2014). Water availability may limit our capacity for carbon sequestration (Falkenmark, 2013). | The area of irrigated agricultural land in NZ almost doubled from 2002 to 2019, and now comprises close to 2% of NZ’s land area (MfE & Stats NZ, 2021). Almost ⅔ of this is in Canterbury to support dairy farming there (ibid). | The value of drought-tolerant and dryland crops may escalate, thus increasing the need to protect them, from pests, weeds and pathogens. |
| **Wildfires**. With climate change, hot dry conditions are expected to result in more and larger wildfire events (Krawchuk et al., 2009). | Fire danger is predicted to increase in the lower North Island, in eastern Marlborough/North Canterbury and eastern Otago/Southland (Pearce et al., 2011). | Wildfires can modify vegetation patterns over large areas, and facilitate dispersal of insects and pathogens by convecting propagules high into the atmosphere (Mims & Mims, 2004). This will especially be relevant to NZ given increased wildfires in Australia coupled with strengthening westerly air flows across the Tasman Sea. |

This summary was derived by reviewing the literature on foresight and global megatrends and highlighting those likely to be greatest concern for biosecurity. An alternative approach was taken by Ricciardi et al. (2017) and Dehmem-Schmutz et al. (2018), who instead surveyed biologists about their expectations for the most influential factors determining future biological invasions. A wordcloud summarising the latter's results is shown at the start of this report, where climate change was identified as the most important factor. Section 5 details our own survey of selected New Zealand biosecurity practitioners and their identified priorities.

## Key messages

- There are many global megatrends that will affect our future, and these are complex and interconnected.
- In some cases, New Zealand's experience of global changes may differ from other parts of the world.
- Border biosecurity will be affected by, and must respond to, many of these trends, perhaps most notably those directly associated with climate change, but also a range of societal, environmental and agricultural challenges.
- Our individual and collective responses to global change must be informed by appreciation of a wide range of values and worldviews. Both technology and traditional knowledge may be needed to overcome some of the challenges of global change.

# Section 2. Future New Zealand climates and landscapes

Primary sector production, including processing and commercialisation, contributed 11.1% to New Zealand's GDP and just over half of the country's merchandise export earnings in 2020 (MPI, 2022). Māori GDP contribution is still dominated by the primary sector, which contributed $2.4 billion in 2018 (Reserve Bank of New Zealand & Business and Economic Research Limited, 2015). The viability of parts of these primary industries is threatened by climate change, with major disruptions to production across the agricultural, horticultural and forestry sectors (e.g., MfE 2020a; MPI 2019; Thorburn et al., 2012; IPCC 2022; The Royal Society of New Zealand Te Apārangi 2016; Ausseil et al., 2019). Some examples are decreased availability of land because of sea-level rise; water due to drought, primary products due to extreme weather, and disrupted supply chains (e.g., through flooding, fire, and changes in seasonality). Extreme weather events, such as flooding or wildfire, can cause extensive damage and disrupt market access (Ministry for the Environment, 2020b), whereas changing seasonality and climate suitability will require farmers to adopt new management, supply and marketing arrangements (e.g., Selvaraju 2012; McCusker et al., 2014; The Royal Society of New Zealand Te Apārangi 2016). Climate impacts will promulgate from directly affected areas and sectors to others through extensive and complex socio-economic linkages (Fitzharris, 2007).

In this section we explore changes in land-use as a response to climate change. However, land-use can also change because of biosecurity incursions which could be driven by climate change, e.g., citrus greening disease wiping out the Florida (USA) citrus industry (United States Department of Agriculture, National Agricultural Statistics Service (USDA-NASS), 2022), or a change in crop rotations (Plant Health Australia (PHA), 2012). Land-use itself can also influence the climate (Dorner et al., 2018), e.g., dense urbanization increases local temperatures due to absorption and re-radiation of solar heat by buildings and paved surfaces (the "heat island effect"; Volk et al., 2017). Land-use, biosecurity and climate change interact, and are also impacted by many other socio-economic, conflict, migration, trade, and policy factors (Rounsevell et al., 2014).

## General climate change predictions for NZ

Climate change projections for New Zealand by the National Institute of Water and Atmospheric Research (NIWA*)* (MfE, 2018) are based on the IPCC 5th Assessment (IPCC, 2013), summarised for Australia and New Zealand by the New Zealand Climate Change Centre Institute (NZCCRI, 2014). Here, we present data based on the 5th Assessment, but updated climate change projections (IPCC 6th Assessment) are currently available in draft form from the IPCC website (https://www.ipcc.ch/reports/). Climate change will vary from place to place throughout the country and from year to year and decade to decade due to natural processes (MfE, 2008). Both natural fluctuations and human-induced (anthropogenic) climate changes need to be considered when approaching the climate change issue.

Due to anthropogenic induced climate change, 21st century New Zealand is likely to be warmer and experience more droughts, floods, storm surges, extreme events and higher sea level (Fitzharris, 2007). There will be some beneficial impacts for farming, forestry, hydro, and irrigation, but many impacts will be negative in terms of water security, coasts, changes in the ocean, built infrastructure, alpine tourism, threats to land-based and freshwater ecosystems and health (Fitzharris, 2007; The Royal Society of New Zealand Te Apārangi, 2016). The Ministry for the Environment (MfE, 2020a) (Chapter 5) identified risks for the natural environment, human, and economy.

Table 2 summarises climate change projections for New Zealand based on very high pre-adaptation risk in 2100 corresponding to the high atmospheric greenhouse gas concentration pathway known as the representative concentration pathway (RCP) 8.5. For more detailed projections at different RCPs and spatial and seasonal variation, refer to Lake et al. (2018) and the report from the NZ Ministry for the Environment (MfE, 2020b) (Appendix B).

The effects will not be uniform throughout New Zealand. Different locations will experience different impacts depending upon combined changes to daily, seasonal and annual weather patterns (Rutledge et al., 2017). Temperature increases will be greater in the North Island than the South Island, and rainfall higher in western parts compared to the eastern parts of both main islands (Thorburn et al., 2012). Future droughts are expected to increase in frequency, but not intensity, and are not expected to affect larger regions simultaneously (Sood & Mullan, 2020). Based on various climate models and RCPs, New Zealand's mean sea level is projected to rise between 0.55–1.36 m over the next 100 years (MfE, 2017).

An interactive website, https://ofcnz.niwa.co.nz/#/nationalMaps, allows users to explore temperature and rainfall projections for New Zealand.

**Table 2**. Summary of climate change projections for New Zealand (MfE 2020, based on data from MfE 2018). All projections are based on representative concentration pathways (RCP) 8.5, the highest modelled atmospheric greenhouse gas concentration pathway, and have a baseline time period of 1996–2005.

| Climate variable | Description of change | Change in 2040 | Change in 2090 |
|---|---|---|---|
| **Temperature** | | | |
| Mean temperature | Overall increase, with greatest changes at higher elevations. Warming greatest in summer and autumn, and least in winter and spring. | +1.0°C | +3.0°C |
| Minimum and maximum temperatures | Overall increase, with greatest changes at higher elevations, particularly for maximum temperature. | Not available | Daily range increases by up to 2°C |
| Number of cold nights (<0°C) | Overall decrease in number of cold nights. | Average 50% decrease | Average 90% decrease |

| Climate variable | Description of change | Change in 2040 | Change in 2090 |
|---|---|---|---|
| Number of hot days (>25°C) | Increase in number of hot days, particularly in already warm regions. | Average 100% increase | Average 300% increase |
| **Rainfall** | | | |
| Average rainfall | Regional and seasonal variation, generally an annual pattern of increases in west and south and decreases in north and east. | Substantial variation around the country, increasing in magnitude with increasing emissions. | |
| Number of dry days | More dry days throughout the North Island and in inland South Island. | Not available | Up to 10 or more dry days per year (about 5% increase). |
| Extreme rainfall events | Increase everywhere. | The 1-in-10-year event up 11% for 1-hour duration, up 5% for 5-day duration. | The 1-in-10-year event up 34% for 1-hour duration, up 15% for 5-day duration. |
| Snow | Large decreases. Snowfall confined to high-altitude or southern regions of the South Island. | Not available | Snow days per year reduce by 30 days or more. |
| Drought | Increase in severity and frequency, especially in already dry areas. | Not available | Potential evapotranspiration deficit increase of about 50 mm. |
| **Other variables** | | | |
| Pressure and wind | Varies with season, on average more northeast airflow in summer. Strengthened westerlies in winter. | Generally, the changes in pressure are only a few hectopascals, but the spatial pattern matters for mean wind changes. | |
| Extreme wind speeds | General increase. Most robust increases occur in the southern half of North Island, and throughout the South Island. | Up about 10% in parts of the country. | |
| Storms | Likely poleward shift of mid-latitude cyclones and possibly a small drop in frequency. | Specific projections not available in New Zealand. | |

| Climate variable | Description of change | Change in 2040 | Change in 2090 |
|---|---|---|---|
| Solar radiation | Varies with location and season. West Coast shows the largest changes by 2090: summer increase (~5%) and winter decrease (5%). | Seasonal changes generally lie between –5% and +5%. | |
| Relative humidity | Overall decreasing, with largest decreases in South Island in spring and summer. | Not available | Decrease of 5% or more, especially in the South Island. |

## Effects of climate change on current crops, acreage, and land-use

Fitzharris (2007) used the IPCC 4th Assessment reports (IPCC, 2007c, 2007a, 2007b) to review the vulnerability of New Zealand to the impacts of climate change. Due to reduced precipitation and increased evaporation, especially in Northland and many eastern regions of the North and South Islands, production from agriculture and forestry is expected to decline in eastern areas distant from major rivers by 2030 (Fitzharris, 2007). On the other hand, in western and southern areas and close to major rivers, benefits to agriculture and forestry are projected because of a longer growing season, less frost and increased water availability (Fitzharris, 2007). These changes are expected to catalyse large geographical shifts in agricultural and horticultural crops (Fitzharris 2007; Ausseil et al., 2016). Tait et al. (2016) used improved modelling to produce new projection maps for New Zealand based on the IPCC scenarios that provides greater spatial details for mountainous areas and new projections of annual precipitation change in the Canterbury foothills and plains. The updated information was used for climate change projections in the Ministry for the Environment report (MfE, 2018).

While Māori-owned farms are likely to be affected in the same way as non-Māori-owned farms, Māori land can be more isolated from infrastructure, and concentrated in areas with less productive land types (Cottrell et al., 2004).

In general, the predicted increased temperatures for New Zealand, and globally, will lead to increased populations and damage of pest species already present in New Zealand, but also provide an environment for new invasive pest species to establish and spread.

The primary sector as a whole has a relatively high adaptive capacity (MfE, 2020b), but different sectors differ in their sensitivity and responses to climate changes. Generally, but certainly in the already drier regions, water will become scarce with probable conflicts between water users, requiring effective governance (MfE, 2020b). Also, for each sector a suite of adaptation actions must be implemented to achieve the desired outcomes, depending on socio-economic conditions for the individual growers (Cradock-Henry et al., 2020).

Horticulture is very sensitive both to water availability at critical times of the growing season, and to intense rain or hail climate (MfE, 2020b; Thorburn et al., 2012). In general, a warmer climate will have benefits for producing subtropical fruits such as avocados and citrus, but there will be both costs and benefits for temperate fruits such as kiwifruit and apples, depending on location. Generally, wine grapes will benefit if sufficient water is available (Kenny, 2001). Relatively minor impacts on horticultural diseases are suggested because of the changes in climate predicted by IPCC 2007, except under the most extreme climate change prediction (upper limit by 2090), which is likely to cause a noticeable increase in risk for the diseases examined (Beresford & McKay, 2012). Climate change will cause negligible change in fruit or berry mass (Clothier et al., 2012). Frame and Reisinger (2016) concluded from the RCP 8.5 scenario that the Kaituna catchment might experience a shift of kiwifruit biophysical suitability to the south due to lack of winter chilling. For wine, Ausseil et al. (2019) predicted that earlier flowering times will inhibit wine quality. An assessment of how kiwifruit growers are managing climate-related exposures, Cradock-Henry (2017) found that most responses were short-term, tactical and reactive, and few of the strategic measures needed for adaptation were in place. As climatic signals become more apparent, there may be a move towards longer-term strategic adaptations (Cradock-Henry, 2017).

Pastoral systems are sensitive to changes in precipitation and temperature, with livestock potentially affected by heat stress in Waikato, Wairarapa and Canterbury Plains (Ausseil et al., 2019). The overall impact of climate change on pasture quality and animal performance is difficult to quantify and will vary by region (Kenny, 2001), but Ausseil et al. (2019) predicted there will be a shift in production towards spring. Models for pasture production under climate change suggest slight increases and a seasonal change in the timing of peak pasture growth (Ausseil et al., 2019; Kalaugher et al., 2017; Keller et al., 2014; Lieffering et al., 2012, 2016; Renwick et al., 2013; Stroombergen et al., 2008). Farm systems models, however, suggest that farm profits will be reduced, especially in Bay of Plenty and Waikato (Kalaugher et al., 2017; Lee et al., 2012). Empirical studies focusing on more fine-scale weather variables predict greater impacts on farm profits (Bell et al., 2021; Pourzand et al., 2020) under business-as-usual. However, New Zealand's production of milk, wool and meat is not likely to be seriously impacted by low to moderate levels of climate change because the challenges can be met by improvements in farm management, pasture and stock genetics, and monitoring technologies (Lee et al., 2013; Kalaugher et al., 2017). Farm types may change, with a likely increase in dairy and decrease in sheep/beef farms, regardless of the trading carbon price (Keller et al., 2014).

In the arable and broadacre sector, industry sensitivity to climate change varies between locations and crops (MfE, 2020b; Teixeira et al., 2012), with a wide range of adaptive measures available to mitigate the threats of climate change (Teixeira et al., 2012). Ausseil et al. (2019) predicted no change in maize yields after accounting for earlier sowing dates because of climate change. Catch crops, i.e., crops grown with the primary objective of catching excess nitrogen in soils, may be less sensitive due to their growth during late autumn and winter (Ausseil et al., 2019). Climate change is likely to be generally positive for arable cropping (Kenny, 2001; Thorburn et al., 2012), and the greatest issue will probably be water availability, particularly in eastern regions (Kenny, 2001). Coastal zone will be impacted by sea level rise, affecting mainly dairy and maize cropping land-use (Frame & Reisinger, 2016).

Forestry is sensitive to: new pests and diseases; changes to the distributions of existing pests and diseases (Watt et al., 2019; Dunningham et al., 2018); fire; and windthrow (higher productivity due to elevated $CO_2$ levels and increased mineralisation of nitrogen may lead to taller and more slender trees) (Watt et al., 2019). Because forestry returns take decades to realise, management and land-use decisions made many years ago determine adaptation options today (Dunningham et al., 2012). Forestry can also be used to reduce net greenhouse gas emissions through conserving existing forest carbon stocks and encouraging additional uptake of carbon in existing and new forests (Wakelin et al., 2020). How much the risks will influence sequestration of greenhouse gas emissions is unknown.

## Land-use change as a result of climate change

Several different economic models have been developed to indicate likely land-use change in response to climate policy.

- Motu's Land Use in Rural New Zealand model (LURNZ) (Dorner et al., 2018) is the only national model. It dynamically simulates land-use change in response to changes in economic returns for dairy, sheep and beef, forestry and scrub, and predicts the potential impacts of climate change mitigation policies, or similar shocks, to these land-use patterns.
- Manaaki Whenua Landcare Research's New Zealand Forestry and Agricultural Regional Model (NZFARM) facilitates a "what if" scenario analysis by showing how changes in environmental policy (e.g., greenhouse gases (GHG) emissions targets) could affect land use in individual catchment areas. It also shows the subsequent spill-over effects on a group of performance indicators important to decision makers and stakeholders. http://tools.envirolink.govt.nz/dsss/the-new-zealand-forest-and-agriculture-regional-model/
- The Agent-based Rural Land Use New Zealand (ARLUNZ) (Morgan & Daigneault, 2015), although not solely based on climate change, examines and resolves complex environmental issues within the rural environment (catchment areas), provides information about how farmers will adapt (both economically and socially) to global change, and reduces vulnerability to resource scarcity.
- Our Land and Water National Science Challenge (https://ourlandandwater.nz/) has a significant portfolio of current research on future land uses.

With no target set for reduction in net land agricultural sector emissions, LURNZ land-use simulations  from 2012 to 2050 predicted a 9.6% increase in dairy area, a 13.6% decrease in sheep and beef, a 55.3% increase in forestry, and an 11.7% decrease in scrub (Table 3. ), with horticulture and all other land held constant by assumption (Dorner et al., 2018). This reference scenario was then compared with two main reduction pathways: a low-ambition (reduction by 15% of 2005 gross agricultural GHGs by 2030 and 25% by 2050), and high-ambition one (30% by 2030 and 50% by 2050), either achieved under targeted growing horticulture scenarios (+40% or +200% by 2050, LURNZ model) or allowing for endogeneous land-use changes between dairy, drystock, arable, horticulture and forest (NZFARM model). Given horticulture and dairy tend to be located on the best land, the horticultural expansion was predicted mainly onto dairy land, hence, there will be less dairying where there is horticultural expansion. A reduction in dairy would lead to lower emissions, thus requiring less forestry expansion to meet GHG mitigation targets. Conversion of sheep and beef land to horticulture would be partly offset by lower emissions prices that put less pressure on sheep and beef farmers to convert land. Forestry expansion is almost entirely driven by the level of ambition, predicted to roughly double with a move from low to high ambition, i.e., proportional to net emissions reductions. Meanwhile, without on-farm mitigation, and with no horticultural expansion, major increases in forestry would be required to meet the net emissions targets. Because scrub mainly competes with plantation forestry, the area of scrub reduces as the level of ambition rises.

At least for the short term, issues like pandemics, war, petrol prices, fertiliser prices, and economics will affect land-use change in production systems more than climate change. The impact of these factors is less important in natural systems (see below, on natural environments), where climate change mitigations are more important in the short term.

**Table 3**. Reference case projections of land use in New Zealand as shares of total land area and change from 2012, derived using LURNZ as per Dorner et al. (2018). The land-use changes in these reference case projections are a result of the commodity price inputs and the existing New Zealand Emissions Trading Scheme (ETS) reward for forestry sequestration.

| **Land use category** | **Share (%)** | | | **Change from 2012 (%)** | |
|---|---|---|---|---|---|
| | **2012** | **2030** | **2050** | **2030** | **2050** |
| Dairy | 7.8 | 8.6 | 8.6 | + 9.6 | + 9.6 |
| Sheep & beef | 30.3 | 27.6 | 26.2 | - 8.8 | - 13.6 |
| Forestry | 7.4 | 9.6 | 11.6 | + 28.3 | + 55.3 |
| Scrub | 6.5 | 6.3 | 5.7 | - 2.7 | - 11.7 |
| Horticulture | 1.8 | 1.8 | 1.8 | 0 | 0 |
| Other | 46.2 | 46.2 | 46.2 | 0 | 0 |

## Future commercial crops for New Zealand

Table 4 summarises some of the new crops which have been identified for cultivation expansion in different parts of New Zealand.

**Table 4**. Potential new crops that might be grown in New Zealand.

| **Crop** | **Reference** |
|---|---|
| Peanuts | Stringleman (2021), Ward and Clothier (2020) |
| Soybeans | Bezzant (2020), Kenny (2001), Ward and Clothier (2020), McAleer (2020) |
| Chickpeas | Bezzant (2020) |
| Quinoa | Bezzant (2020), McAleer (2020) |
| Oats | Bezzant (2020) |
| Buckwheat | Bezzant (2020) |

| | |
|---|---|
| Sorghum | Kenny (2001), Ward and Clothier (2020), McAleer (2020) |
| Pineapple | Coriolis (2020), Radio New Zealand (2021) |
| Banana | Coriolis (2020), Radio New Zealand (2021) |
| Rice | Kenny (2001) |

The success of new commercial crops will be strongly dependent on market conditions in the future (mostly economics), and the true effects of climate change in the different regions. As with current crops, water (irrigation) will determine which new crops can be grown and where plant breeding in currently grown crops can mitigate some of the challenges and provide for drought, salt, and pest and disease resistant cultivars, for example, and genetically modified versions of these crops may be available in the future.

The realisation that our food systems are possibly already operating beyond planetary boundaries, however, has triggered calls for a more fundamental transformation of our agriculture (Webb et al., 2020). Recent events like the COVID-19 pandemic, the Suez Canal blockage, or the war between Russia and Ukraine have further exposed supply chain fragilities, reinforcing the perceived need to revise some of our food production practices. Regenerative agriculture for instance, is promoting radical changes in our ways of living, working, and farming, and is seen by some as a sustainable solution to manage limited planetary resources and cope with both current and forecasted environmental and societal challenges. A recent study involving participants from various New Zealand primary production sectors identified 15 major themes that can be used to describe what regenerative farming outcomes might look like (Grelet et al., 2021): social wellbeing, soils, integrated circular systems, access to markets, productivity and profitability, mindset, biodiversity, waters, long-term and te ao Māori culture/values, air and climate change solutions, regenerative agriculture definition and evidence, food quality and safety, animal welfare, resilience, and farm integration in landscape.

Nonetheless, barriers to change are encountered where there are people involved in making decisions. Barriers to changing land use were categorised into seven groups by Dorner et al. (2018):

1. information
2. market structure and institutions
3. regulation and policy
4. risk and uncertainty
5. externalities
6. efficiency (where a financial profitability test fails to correctly measure the economic impact on the farmer), and
7. behavioural factors (e.g., first cost bias and habitual behaviour), which were the strongest barriers.

Land-use change for Māori is more complex as there are many 'owners' of the land, there are cultural differences between regions, and there may be an inability to finance investments (Dorner et al., 2018). Māori also see risk in participating in schemes, where future control and retention of the land is thought to be at risk (Dorner et al., 2018).

The combination of global climate change and new crop types or changes in land-use, including intensification, will alter pest threat profiles. Additionally, currently innocuous invertebrate species may become damaging. For example, climate change is leading to plantain becoming a more important component of pastures, resulting in turn to the emergence of native plantain moths *Scopula rubraria* and *Epyaxa rosearia* as serious economic pests (Gerard et al., 2018). Biosecurity risk management will need to protect against whole suites of new pests that affect these new landscapes.

## Climate change and natural ecosystems

Observed impacts of climate change on terrestrial and ocean ecosystems have a high or very high confidence, with shifts in species' ranges and a change in phenology in terrestrial ecosystems (IPCC, 2022a). Changing climatic conditions will worsen a range of existing threats to and pressures on New Zealand's natural environment (Ausseil et al., 2016; Macinnis-Ng et al., 2021; McGlone & Walker, 2011; MfE, 2020b), however, McGlone and Walker (2011) add that this may be true in the long term, but that in the short term the risks associated with combating climate change are a greater risk to biodiversity. Macinnis-Ng et al. (2021) summarised the results of their Aotearoa New Zealand case study as "in addition to sea-level rise, most ecologically meaningful impacts of climate change on biodiversity responses are indirect and due to exacerbation of existing threats, including the impact of invasive species as well as the loss and fragmentation of habitat."

There are still knowledge gaps related to climate change and the natural environment (MfE, 2020a). Detailed knowledge on climate change threats to individual sites and species is generally lacking in New Zealand (Halloy & Mark, 2003, MfE 2020b, Macinnis-Ng et al., 2021), reflecting past funding shortfalls for climate change-related research and/or sites subject to long-term monitoring and study. Because of this, most of the understanding for different groups of ecosystems and/or species comes from detailed studies of a few sample systems or species, extrapolated across the broader natural environment domain. For example, Halloy and Mark (2003) showed with species-area relations models that 40–70 species of native alpine plants could become at risk if the present mean temperature of ~0.6°C higher than in 1900 were maintained. A large pool of exotic plant species would also become at risk under this scenario. At the same time, other exotic species could augment the resulting flora. Macinnis-Ng et al. (2021) point to indirect effects of climate change, such as rising temperatures resulting in an extended overlap of the flowering of native alpine plants and invasive plants, leading to increased competition for pollinators and potential lower seed production. There may also be fewer cool places to take refuge from predators for alpine birds, and the freezing tolerance of insects may be disrupted, making them less likely to survive unpredictable exposure to freezing temperatures (Wharton, 2011). In the lowland case study by Ausseil et al. (2016), warmer temperatures were forecast to increase the range expansion of pests into the study area, causing a reduction in abundance or loss of native species.

Another constraint to researching the effects of climate change on natural ecosystems is New Zealand's poor management of spatial biological data (Halloy & Mark, 2003). A report published by the Ministry for the Environment (MfE, 2020b) concludes, "New Zealand lacks a single easily accessible repository for distribution data (as provided for example by the Atlas of Living Australia (www.ala.org.au))". The report sums up the situation in New Zealand with "Critical data are stored in a disjointed fashion that lacks coordination, with access constrained by the competitive model used to fund and manage New Zealand's research organisations."

## Key messages

- Climate change predictions vary for each current growing region.
- Different sectors and crops are affected differently by projected changes in climate.
- Future crops and landscapes will be threatened by a different suite of pests and pathogens which may or may not already be present in New Zealand.
- Natural environments have not received as much attention as crops and could be vulnerable to loss of endemic species.
- Climate change, land use and biosecurity are interrelated in a dynamic interplay, making for complex system behaviour.

# Section 3. Global pest movement and distributions

Expansions of invasive species outside their native ranges have substantially accelerated in the twentieth century due to the expansion of a globalised economy and associated increasing movements of people and international trade (Seebens et al., 2018; Pyšek et al., 2020). Recent increases in new introductions of non-native species have shown no signs of saturation, and increases appear to be accelerating for many taxonomic groups including pest organisms such as weeds, insects, and microbial pathogens (Pyšek et al., 2020; Seebens et al., 2017). Moderate to strong increases of invasive species arrivals are predicted in almost all world regions. Australia and New Zealand are part of only a handful of countries where introduction rates are predicted to decline but remain positive (Seebens et al., 2021). Nonetheless, in the long term, it can be expected that most sufficiently mobile species will be able to track their favoured conditions (climate, host plants) everywhere around the globe, including in new areas where climate or land use change become favourable. At ≥4 °C warming, major biome shifts are predicted to result from climate change, affecting up to 35% of global land area (IPCC, 2022a).

With a general warming trend, plant and animal distributions generally shift poleward or, on land, upslope to higher elevations (Parmesan & Yohe, 2003; Walther, 2010; Wang et al., 2017). The work summarised in the Assessment Report (AR6) published by the IPCC Working Group II indicated species redistributions are already happening, with multiple independent lines of evidence showing approximately half of the species assessed worldwide are currently experiencing range shifts to northern or southern latitudes, to higher altitudes, or both (IPCC, 2022a). Milder winters arguably play a role in the northern range expansions observed for several species of birds and butterflies in Europe (Parmesan, 2006), and more complex mechanisms like changing snow cover have been identified to provide thermal escapes and allow other species to expand at higher latitudes in North America (Streifel et al., 2019).

In this context, it is expected that new invasions will be facilitated due to the combined effects of climate change and amplification of international trade (Seebens et al., 2015). Part of the high species diversity of the tropics, for instance, is expected to spread poleward into large tracts of currently temperate lands. Certain world regions may also have particularly high potential for species diversifications. Areas of intermediate precipitation, marked seasonality, and rugged topography are thought to favour species migrations, leading to repeated events of speciation and extinction, i.e., the “cradle of evolution” hypothesis (Vasconcelos et al., 2022). The combined effects of increasing biological invasions, land use change, and climate change, may amplify this phenomenon, leading to increasing pressures on the environment and human livelihoods (Pyšek et al., 2020; Millennium Ecosystem Assessment 2005). With the breakdown of natural biogeographical barriers, the impacts of both current and new pests could be amplified. Novel associations between plant pathogens and insect vectors, for instance, have already started to create new patterns of plant disease emerge (Lu et al., 2016; Slippers, 2020). These future events are particularly hard to predict (e.g., Ploetz et al., 2013), and will most likely turn into significant plant health challenges this century.

## Global species movement drives biological invasions

The successes and failures of biological invasions are primarily determined by the rates at which invaders arrive in new areas,  (a.k.a. “propagule pressure”) (Levine & D’antonio, 2003; Seebens et al., 2018), the biological and ecological characteristics of these species (a.k.a. “invasiveness” traits, such as survival and reproductive performance), and the characteristics of the receiving environment that affect their ability to locally establish (a.k.a. “invasibility”, the biotic and abiotic characteristics of the receiving area) (Early et al., 2016; Hui et al., 2016; Theoharides & Dukes, 2007). With increasing anthropogenic pressures, including global trade, land use modifications and climate change, there is little doubt we will see further changes affecting some, if not all, of these three components (Dukes & Mooney, 1999; Hulme, 2017; IPCC, 2022a; Walther et al., 2009). The challenge for biosecurity practitioners is therefore to anticipate future evolutions in pest pressures, and, when possible, to prevent future pest introductions to protect valued crops and environments (Simberloff et al., 2013).

Most challenges in preventing biological invasions can be amplified by other societal, agricultural, or environmental changes. First, global warming and other climate disturbances may increase the abundance of invasive organisms in their native and invaded regions. Second, changes in international trade and travel have potential to alter associations between invasive organisms and invasion pathways, including infestation rates and the ability to survive transport conditions. Third, with increasing potential for most invasive organisms to be transported elsewhere, effective pest risk analysis will become increasingly important.

In this section, we discuss the effects of global change on pest movements and the potential for increasing arrivals of pest species in new countries or continents. However, only a small fraction of species arriving in new areas will establish due to habitat and climatic constraints, Allee effects and random events. Future pest introductions to New Zealand, including how they might be predicted and the consequences of global change for biosecurity management, are discussed in Section 4.

## Pest abundance in native and invaded regions

In native ranges, top-down regulation (typically from natural enemies) generally combines with bottom-up regulation (e.g., from host plants for herbivores) and competition to limit organisms’ reproductive success and survival and maintain populations at relatively low levels. Stochastic or periodic influences, such as weather events, climate stresses or enemy releases, may unbalance trophic interactions leading to pest population increases, which in turn can result in higher risks of contamination of exported commodities. Synchronous population increases can occur at different spatial scales, from local to continental (Koenig, 2002). Considering forest insects for instance, bark beetles increase in large numbers following storms that create massive amounts of suitable host material (Hlásny et al., 2021), whereas defoliating insects, such as Lepidoptera, tend to outbreak in association with climatic and other factors (Myers, 1998). The 2018 drought and storms in Europe for instance, have been linked to sudden bark beetle epidemics and high spruce tree mortality. This has caused an increase in timber stocks and a fivefold surge in the whole European flow of wood exports to China (Pureswaran et al., 2022). The probability of introduction of bark beetles and other non-native species from Europe to China could have been particularly high during that period.

Similarly, contamination of traded goods by caterpillars or moth egg batches could be particularly high during outbreaks periods.

The abundance of non-native pest species in invaded areas can also fluctuate widely. Many insects and plant pathogens of minor significance in their native ranges only gain pest status in introduced areas where they may lack natural enemies and be exposed to novel combinations of hosts and environmental conditions (Jactel et al., 2019; Wingfield et al., 2015). With accelerating rates of pest invasions to new continents, some pests can become particularly widely distributed and may be picked up more frequently by global transportation networks (Pysek et al., 2010). This phenomenon is amplified when invasive species become highly abundant locally in association with increased availability of suitable host material and favourable climatic conditions (Williams & Liebhold, 2002). Numerous examples have been documented: For instance, the extended cultivation of *Eucalyptus* trees outside of Australia has facilitated the rapid dissemination of many pests and pathogens associated with this plant group (Wingfield et al., 2008).

## Pest associations with transportation pathways

Infested agricultural products are the most common transport mode for many weeds, pests and plant pathogens. Infestation can occur during production, processing, or in transit to ports. Many organisms also “hitchhike” with movements of non-host material. Such associations are particularly difficult to manage because hitchhiking pathways are so diverse, including the external and internal surfaces of vehicles (air, maritime and land), sea containers, air containers, smaller traded items, and travellers’ personal items. Phytosanitary inspections and treatments are applied to deal with most pathways, with greatest emphasis on agricultural products and certain other high-risk categories of host and non-host items (Ormsby & Brenton-Rule, 2017). Treatment aims to eliminate or reduce contamination, but use varies between countries (Eschen et al., 2015). Some pathways are particularly difficult to manage, and infestation rates may remain high despite treatment (Haack et al., 2014).

Some changing patterns of biological invasions are related to shifts in international trade. For instance, increasing trade of plants for planting and other exports from Asia to other continents has led to more frequent invasions by pests from countries like China and India (Roques et al., 2010; Turbelin, Malamud, & Francis 2017). Likewise, invasions by non-native forest insects of Asian origin have increased in recent decades in North America (Brockerhoff & Liebhold, 2017; Liebhold et al., 2017; Langor et al., 2009) and Europe (Roques et al., 2020), but not in Australia (Nahrung & Carnegie, 2020) and New Zealand (Brockerhoff et al., 2006; Brockerhoff & Liebhold, 2017).

Changes in global trade can be gradual or quick. Economic relationships and trade agreements have potential to rapidly modify trade patterns with knock-on effects on pest movements. Trade bans associated with phytosanitary regulation, or alternatively, elevated costs to avoid such bans, are critical factors affecting trade destinations for log export (Self & Turner, 2009; Turner et al., 2007). Similarly, air passenger numbers can surge and ebb in response to internationally significant events, creating temporary changes in biosecurity risk.

Climate change may create flow-on effects on the dispersal of organisms between countries (Luck et al., 2014). Existing trade routes could be disrupted as more frequent storm conditions are expected in some regions, whereas new routes such as the Northwest Passage are likely to open due to loss of sea ice in the high Arctic. Irrespective of climate change, constantly evolving trade routes may drive significant changes in the identity and numbers of forest insects transported globally. These changes could result from shifts in origins, destinations or contamination levels of transported commodities and from differential survival during transit. Gray (2017) used a model of trade routes to show the combined effects of trade ship itineraries and global warming on risk of spongy moth invasions. For insects, as well as for most other invasive organisms, changes in temperatures and other conditions in transit have profound impacts on survival rates and the number of individuals arriving at destination. Species that are transported within host plants or other material (e.g., pathogens or woodborers), or that can hitchhike for particularly long periods in a developmental hiatus or diapause (e.g., as eggs, pupae, or diapausing stages for insects), have greater potential for survival upon transport (Meurisse et al., 2018).

Climate change effects on the seasonality of trade, and increased arrivals of potentially infested plants or woody material in periods of the year when establishment can be facilitated is another concern. Colunga-Garcia et al. (2013) investigated how live plants imported to North America contribute to propagule pressure of agricultural and forest pests at different US ports. Their results showed striking seasonal variation in plant imports for the northernmost entry locations usually associated with significant reductions in import volumes in spring. With climate change, milder winters in some countries might affect annual plant import cycles, affecting the number and timing of pest arrivals. The consequences of seasonal changes in pest entries on establishment are difficult to predict. For instance, reduced propagule pressure could be expected in certain areas, while expanded durations for pest entries may increase establishment probabilities (e.g., greater chance of matching a suitable climate).

Besides the timing of invasive species arrivals, the location of these arrivals could be affected by climate change and other future trends. Ports, urban centres, and peri-urban areas are the most likely first points of entry for traded commodities or international travellers. They are also generally identified as the most likely places for non-native species introductions. However, the risk associated with these “entry” locations is constantly evolving. Ports, and industrial and commercial areas may expand or specialise, affecting the nature and levels of associated biosecurity threats. They can also occasionally get in closer contact to preferential habitats for invasive species (e.g., closer to large urban parks, agricultural areas or natural environments). New “risk” locations can likewise emerge, a phenomenon that is likely to be favoured by sea level rise and other effects of climate and global change. For instance, it is predicted that certain seaports will quickly see their traffic reduced to the profit of others. Additionally, for many invasive species, introduced populations are themselves responsible for new introductions, in a process whereby initial invasive populations serve as the source of additional invasions. This self-accelerating process is also known as the “bridgehead effect” (Bertelsmeier & Keller, 2018).

Natural dispersal is a more conventional phenomenon to explain the extension of species range when environmental conditions become suitable for expansions. It is more common between neighbouring countries or regions on the same continent, or between nearby islands. However, there are several examples of invasive species that have successfully dispersed by natural means over long distances (e.g., myrtle rust, fall armyworm). This can be wind or sea currents, but also by means of animal vectors. Although invasions via natural dispersal have occurred for millennia, human trade and travel have increased the rate of biological invasions by several orders of magnitude.

## Key messages

- Introductions of non-native species outside their native ranges have substantially increased in recent decades, with no signs of saturation, even in countries that implement stringent biosecurity protocols like New Zealand.
- Biological invasions principally result from human factors, strongly associated with long-distance exchanges of traded commodities and international travels. The expansion of agriculture and increased cultivation of ornamental plants have also triggered range expansions into locations where weeds and pests would never have been able to establish before.
- Under climate change and other agricultural or societal developments, international exchanges will most likely be altered, affecting rates of entries for certain categories of invasive organisms and source regions. More frequent and damaging extreme weather events will also increase the movement of certain species propagules over long distances and across physical barriers. However, while there is accumulating evidence for the role of climate change in expansions at the borders of native ranges, there is only limited evidence for direct effects of climate change favouring remote invasions.
- Speculatively, the most mobile pests should be able to establish in all locations where they find suitable conditions for establishment. But they can only do so if their propagule pressure - the rate at which individual propagules are introduced at a particular location - exceeds a certain threshold. Specific adaptive evolutions of invasive organisms to exploit novel conditions are also extremely difficult to predict.

# Section 4. Future New Zealand pests

Edney-Browne et al. (2018) compiled a list of 1477 non-native insects that have become established in New Zealand to date, though there are numerous additional non-native species in NZ that remain to be added (Phillips, Turner, unpub. data). Similarly, Sikes et al. (2018) have identified 466 species of plant pathogens that were presumably introduced from overseas, and Brandt et al. (2021) listed 1798 non-native plants that have naturalised in New Zealand. The costs attributed to managing the most damaging of these species are already substantial (Diagne et al., 2021; Ferguson et al., 2019; Nimmo-Bell, 2009; Bertram, 1999). Nevertheless, results from pest risk analyses for economically important plants such as grasses, clovers and forage crops (Phillips et al., unpub. data), *Pinus radiata* and Douglas-fir (Herron et al., 2020; Turner et al., unpub. data) and kiwifruit (Stringer et al., unpub. data) indicate there are thousands more foreign pests of plants that could establish in New Zealand given the opportunity. This expectation is consistent with invasion rates globally, which show no sign of saturating (Seebens et al., 2017; Seebens et al., 2021). Inevitably, a proportion of the non-native species that establish in New Zealand in the future will have adverse consequences for conservation (Brockerhoff et al., 2010; Phillips et al., 2020), cultural (Bradshaw et al., 2020), amenity (Townsend et al., 2008) and production (Ferguson et al., 2019) values. This expectation is also consistent with the predicted impacts of biological invasions globally (Pysek et al., 2020).

A critical challenge for border biosecurity in New Zealand is to recognise the new pest organisms that are most likely to evade its border biosecurity processes and may become established. Such recognition facilitates effective pre-border phytosanitary regulation, border screening of imports and passengers, and post-border preparedness, surveillance, and response.

## Forecasting future pest establishments in NZ

Ricciardi (2007) reviewed the characteristic features of modern human-facilitated invasion events: (i) declining effects of geographic barriers and increasing frequencies of long-distance dispersal events; (ii) large variations in mechanisms and routes of dispersal; and (iii) increasing species diversity and propagule numbers per event. Together these characteristics provide potential for: Continuous large scale—sometimes nearly global—invasion events (see also Section 3); homogenisation of global biodiversity; the emergence of new associations between natural enemies, herbivores, pathogens, and plants; and synergetic disruptions with other consequences of global change. Climate change will probably disturb some previously identified invasion patterns and increase the difficulty of predicting which species are New Zealand's greatest biosecurity risks. As the climate warms, the country is also expected to become more suitable for the establishment of tropical and subtropical pests for whom summer in the far north of New Zealand may be the current southern extreme of their distributions. A similar pattern is expected on other temperate islands such as the United Kingdom (Cannon, 1998).

While it is impossible to precisely predict which foreign species will become established in New Zealand, when they will arrive, and how much harm they will cause, we can learn from the non-native organisms that have managed to establish to date. For instance, there have been some consistent patterns in New Zealand invasions to date, which suggests it should currently be possible to roughly rank non-native species that are absent from New Zealand by the likelihood they will establish there in the future. For example, non-native insects that have become established in New Zealand often satisfy at least three of the following four criteria (Phillips & Vink, 2013):

- Their overseas distributions have climatic similarities with New Zealand.
- They are established in non-New Zealand locations outside their native range.
- They are present in Australia.
- Other members of the same genus are present in New Zealand.

Many other attributes also characterise species that successfully migrate to new regions (Brockerhoff & Liebhold, 2017; Phillips & Vink, 2013; Vilardo et al., 2022). The most successful invasive species often share attributes that promote their survival in transport and upon arrival under a wide range of environmental conditions (e.g., high thermal tolerance, and dormancy or quiescence behaviours), and facilitate establishment from small founding populations (e.g., polyphagy, asexual reproduction, sib-mating). Besides species' attributes, survival and establishment probabilities will also be influenced by pathway characteristic and phytosanitary measures (see also Section 3).

Analysis of interception data can help to understand the composition, entry rates and success of species arriving on different invasion pathways (Turner et al., 2021; 2020). However, interception data generally suffer from several biases such as surveys focusing both on particular commodities and a small number of quarantine pests. For instance, insects belonging to economically unimportant groups are either seldom searched for or not identified to species, and interception data are even more scarce for microorganisms and soil borne pests and weeds (McNeill et al., 2017, 2011). Based on data collected at US ports of entry and border crossing, Work et al. (2005) estimated that even rigorous inspections detected only 19% to 50% of imported non-native species.

## Climate change impacts on future establishments and consequences

Border biosecurity risk is the product of establishment probability times the consequence of establishment. Climate change may influence non-native species' establishment probabilities in New Zealand by:

- Influencing species occupied and potential geographic ranges overseas (Diez et al., 2012; Hill et al., 2016). Difficulties modelling species distributions under climate change are discussed by Araújo and Rahbek (2006).
- Changing spatial and temporal patterns of pest outbreaks overseas (Haynes et al., 2014), which will influence the probability pests could infest human transport pathways.
- Altering land use patterns overseas (Borrell et al., 2020).
- Influencing patterns of international trade and travel (Anderson & Strutt, 2014).
- Changing NZ's climatic suitability for species establishment.
- Changing land use patterns in New Zealand (Section 2).
- Varying volumes, types and geographic origins of goods imported to New Zealand (Kompas et al., unpub. data).

- Changes to large scale (e.g., oceanic) wind and water currents that influence species' patterns of natural dispersal.
- Extreme climatic events, which may facilitate species' dispersal and establishment in formerly uncolonised regions (Diez et al., 2012).
- Awakening sleeper pests in foreign countries (Duursma et al., 2013), which will increase the probability they could reach New Zealand via global trade and travel.

And climate change will influence the consequences of non-native species establishment in New Zealand by altering:

- The damage caused by crop pests, which may be exacerbated by climate warming (Deutsch et al., 2018). Increased $CO_2$ will also influence pest damage levels (Fajer et al., 1989).
- New Zealand's climatic suitability for non-native species' population growth and dispersal (Bale et al., 2002; Beresford & McKay, 2012; Christie et al., 2020; Wakelin et al., 2018; Watt et al., 2019).
- Relative environmental, cultural, amenity and economic values of different plant species and land uses (e.g., NZ CCC's draft advice to plant extensive native forest).
- Plant composition such as C: N ratio (Ainsworth & Long, 2005; Ainsworth & Rogers, 2007; Fajer et al., 1989).
- Land use patterns in New Zealand, which will be influenced by climate (Baisden et al., 2008; MfE, 2018), irrigation and sea level (Christie et al., 2020; Paulik et al., 2020). See references in Table 2 of (Ausseil et al., 2016).
- Transport and tourism modes and patterns within New Zealand (Christie et al., 2020), which may influence rates and patterns of pest dispersal.
- Opportunities for establishment in areas disturbed by extreme events such as flood, drought and fire (Christie et al., 2020; Diez et al., 2012).
- The abundance, diversity and potential biocontrol efficacy of non-native species' natural enemies in New Zealand (Fajer et al., 1989; Gerard et al., 2010; Gerard et al., 2013; Gerard, Kean, et al. 2013; Schreven et al., 2017).
- The economics, acceptability and efficacy of different pest management options that have large greenhouse gas footprints such as synthetic pesticides (Audsley et al., 2009; Heimpel et al., 2013), including compensating for pest-induced yield losses by applying fertiliser (Wear & Andrews, 2005).
- Use of both cut and carry livestock feeds and imported livestock feeds.

## Biosecurity investment

The long-term average rate of establishment of accidentally introduced fruit crop pests in New Zealand is about seven per decade (Charles, 1998). This rate is even higher for other sectors such as forestry (Edney-Browne et al., 2018; Sikes et al., 2018; Turner et al., 2021). If, as expected, pressures on national borders from foreign pests increase with climate change and the characteristic features of pest movement described above, then greater investment in risk mitigations such as surveillance will be required to keep pace with escalating risk (Carnegie et al., 2017). The return on such investments is often large (Carnegie et al., 2017).

Biosecurity to prevent new incursions will use increasingly sophisticated modelling tools (Butikofer et al., 2018; Diamond et al., 2012), including future climate projections that have been downscaled to the level of individual farms (Clark, 2012). Work is underway to elucidate the options available to New Zealand's various plant-based industries to adapt to climate change (Clark et al, 2012; Clark et al., 2012a, 2012b; Clothier et al., 2012, 2018; Dunningham et al., 2012; Dynes et al., 2010; Kalaugher et al., 2013, 2017; Kenny, 2011), and how those adaptations might perform in the context of future global trade (Daigneault, 2019). Significant further work is needed to help New Zealand's plant-based industries successfully adapt (Cradock-Henry et al., 2019). The pressure on industries to adapt to climate change will compound with other environmental pressures (Foote et al., 2015). Precisely how industries adapt will influence their exposure to different biosecurity risks (Heeb et al., 2019).

Recommendations for protecting agriculture from both current and future pests under climate change (Heeb et al., 2019) boil down to implementing accepted principles of integrated pest management and border biosecurity more comprehensively and effectively than current norms. However, use of some common pest management practices such as applying pesticides and fertiliser (to help plants compensate for pest damage) may become increasingly constrained because they themselves contribute to greenhouse gas emissions (Heimpel et al., 2013; Wear & Andrews, 2005).

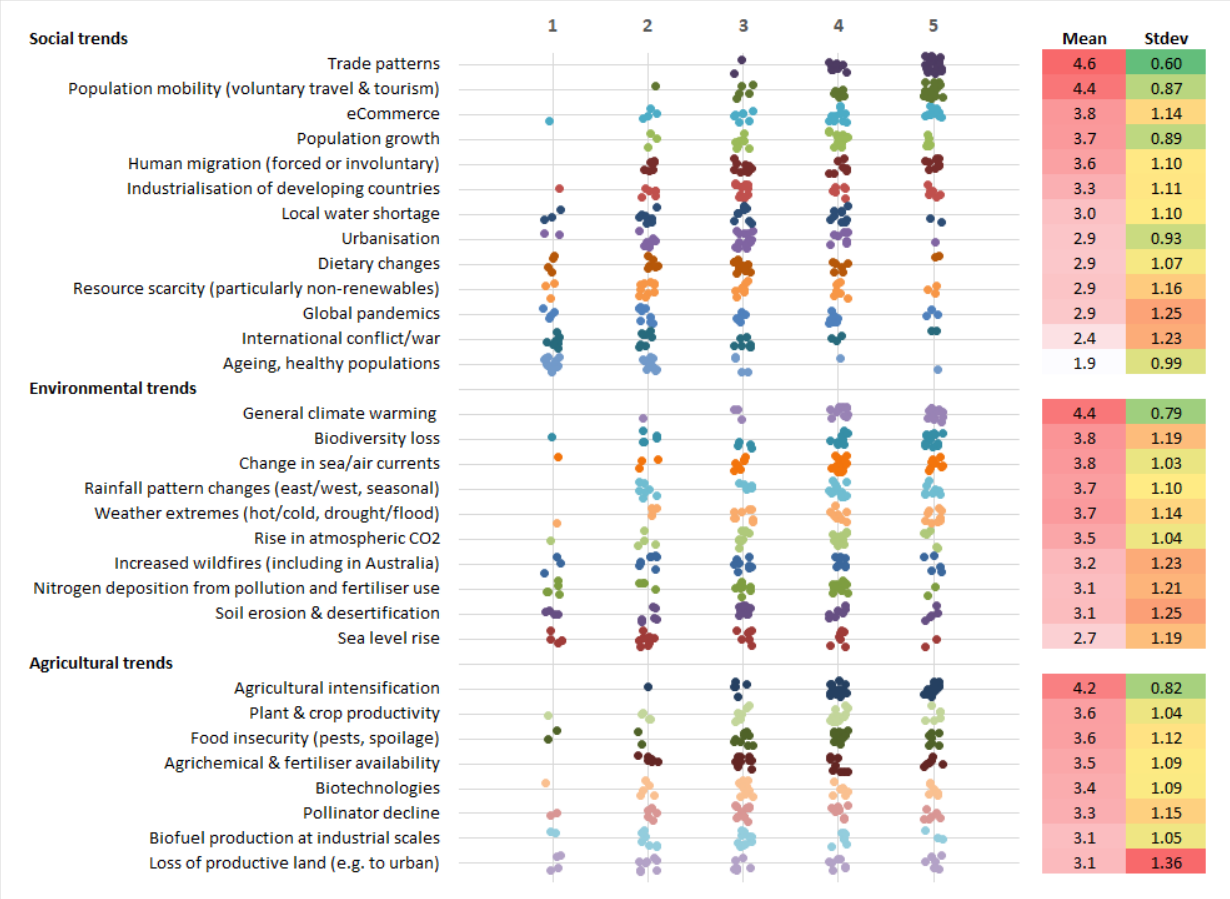
## Key messages

- Hundreds of non-native species have already established in New Zealand, and many more are expected to be introduced in the next decades.
- We need to understand which ones have an opportunity to arrive at our borders, which ones are more likely to establish, and which ones among these are more likely to become harmful, then implement effective risk mitigations.
- New Zealand invasions have exhibited some consistent patterns, which can be used to guide risk assessments. However, the extent to which these patterns will be disrupted remains uncertain and should be monitored.
- Interception data from New Zealand and other countries can provide useful information about the pool of invasive species moving globally, and which ones are arriving at our borders. However, interceptions tend to lag establishments rather than predate them.
- Climate change can have multiple direct and indirect consequences on the arrivals of non-native organisms, their establishments, and potential impacts.

## Section 5. Stakeholder priorities for future research

In May and June 2021, we surveyed and discussed the emerging threats of global change with government, Māori, primary industry and research stakeholders in New Zealand. We asked them to rate each of the trends from Figure 1 and Table 1 (excluding flooding, which was separated from other effects later) on a five-point Likert scale (1 = low, to 5 = high) with respect to their potential implications for the integrity of New Zealand's biosecurity. We also invited free-text comments and observations. The survey was delivered as a Google form, accompanied by background information (Table 1), then discussed at a workshop a few days later.

We received a total of 33 responses to the survey, comprising 19 self-identified as researchers (58%), seven as primary industries (21%), six as central government (18%) and one as Māori (3%). Figure 2 summarises the survey responses. The most important factors (mean > 4.0) were identified as trade patterns, general climate warming, population mobility, and agricultural intensification. Other trends of concern (mean > 3.6) included eCommerce, biodiversity loss, changes in sea and air currents, population growth, rainfall patterns, and weather extremes. The greatest disagreement (highest standard deviation) was over the importance of loss of productive land.



| | Mean | Stdev |
|---|---|---|
| **Social trends** | | |
| Trade patterns | 4.6 | 0.60 |
| Population mobility (voluntary travel & tourism) | 4.4 | 0.87 |
| eCommerce | 3.8 | 1.14 |
| Population growth | 3.7 | 0.89 |
| Human migration (forced or involuntary) | 3.6 | 1.10 |
| Industrialisation of developing countries | 3.3 | 1.11 |
| Local water shortage | 3.0 | 1.10 |
| Urbanisation | 2.9 | 0.93 |
| Dietary changes | 2.9 | 1.07 |
| Resource scarcity (particularly non-renewables) | 2.9 | 1.16 |
| Global pandemics | 2.9 | 1.25 |
| International conflict/war | 2.4 | 1.23 |
| Ageing, healthy populations | 1.9 | 0.99 |
| **Environmental trends** | | |
| General climate warming | 4.4 | 0.79 |
| Biodiversity loss | 3.8 | 1.19 |
| Change in sea/air currents | 3.8 | 1.03 |
| Rainfall pattern changes (east/west, seasonal) | 3.7 | 1.10 |
| Weather extremes (hot/cold, drought/flood) | 3.7 | 1.14 |
| Rise in atmospheric CO2 | 3.5 | 1.04 |
| Increased wildfires (including in Australia) | 3.2 | 1.23 |
| Nitrogen deposition from pollution and fertiliser use | 3.1 | 1.21 |
| Soil erosion & desertification | 3.1 | 1.25 |
| Sea level rise | 2.7 | 1.19 |
| **Agricultural trends** | | |
| Agricultural intensification | 4.2 | 0.82 |
| Plant & crop productivity | 3.6 | 1.04 |
| Food insecurity (pests, spoilage) | 3.6 | 1.12 |
| Agrichemical & fertiliser availability | 3.5 | 1.09 |
| Biotechnologies | 3.4 | 1.09 |
| Pollinator decline | 3.3 | 1.15 |
| Biofuel production at industrial scales | 3.1 | 1.05 |
| Loss of productive land (e.g. to urban) | 3.1 | 1.36 |

**Figure 2**. Summary of stakeholder survey responses for how important different aspects of global change are likely to be for border biosecurity.

The survey free-text responses and workshop discussions elaborated and expanded on these priorities. We mapped the trends into five spheres of biosecurity influence, each aligned with different aspects of risk assessment (Figure 3).

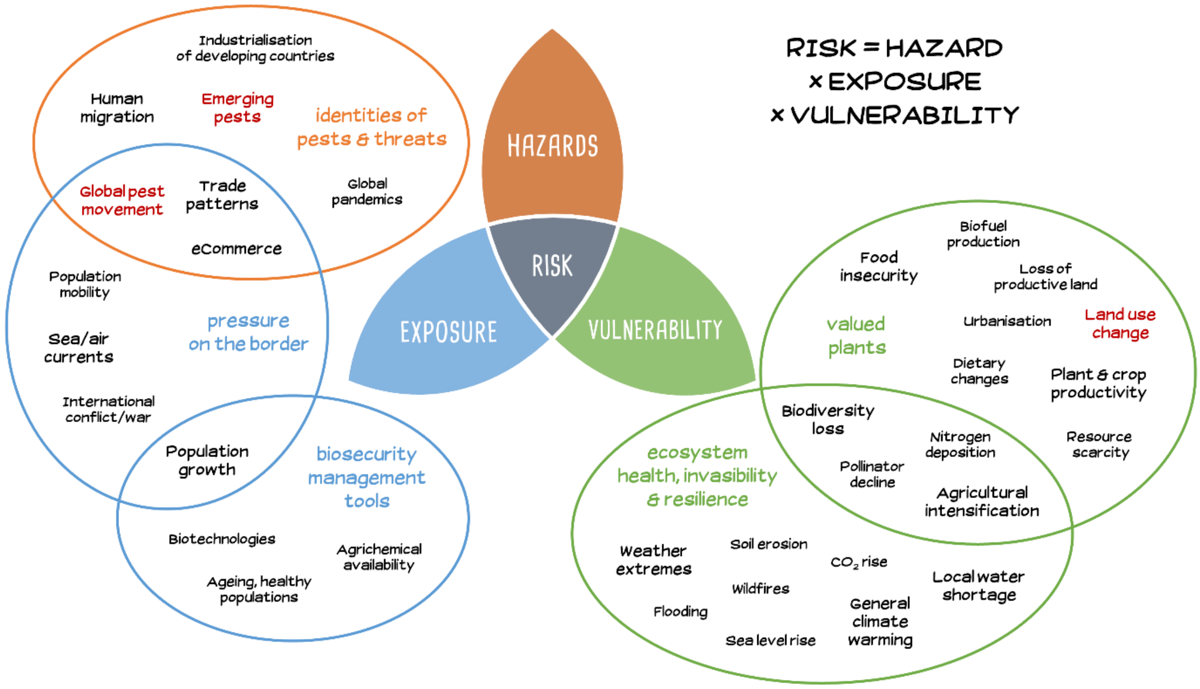


**Figure 3**. Map of future trends by the aspect of biosecurity risk they are most likely to influence. The red highlighted areas were identified at the start of this project as the three key proximal drivers of change affecting NZ biosecurity and are discussed in previous sections of this report.

From these five general areas of biosecurity influence, we identified four priorities for future research around climate change and other global megatrends affecting our biosecurity system:

1. Future pests and threats
2. Changing pest pressures on the border
3. Vulnerability of host plants and ecosystems
4. Evolving biosecurity management tools and constraints.

The first three categories align with the general principle of defining risks by evaluating hazards, exposure and vulnerabilities, whereas the fourth addresses more operational drivers of change, such as new technologies and policies, which may affect our modes of operation and ability to perform biosecurity interventions.

The four priorities generally match the five nonexclusive consequences of climate change for invasive species identified by Hellmann et al. (2008):

1. Altered distribution of existing invasive species
2. Establishment of new invasive species (identities of pests and threats)
3. Altered transport and introduction mechanisms (pressure on the border)
4. Altered effectiveness of control strategies (biosecurity management tools)
5. Altered impact of existing invasive species (valued plants and ecosystem health, invasibility & resilience).

Examples of gaps to our biosecurity system and potential research areas to develop are provided below. Some of these examples apply to more than one identified priority.

## Future pests and threats (Hazards)

Future accidental pest and pathogen introductions are inevitable. Most should have negligible consequences, but some will negatively affect New Zealand's natural and/or productive systems. There are multiple lists of overseas biosecurity hazards that are held by MPI, CRIs, industry sectors and other organisations in New Zealand. These lists often comprise the most damaging pest species overseas but may not consider attributes that make some species more likely than others to arrive and establish in NZ. Further, most hazards are prioritised based on their potential economic impacts on primary production, while threats to our natural and non-productive ecosystems are comparatively underappreciated.

Priorities for further work include:

- **Develop methods for considering potential expansions of host plant ranges and geographic distributions in pest risk assessments.** The distributions of many pests will increase, thus increasing their probabilities of introduction to NZ. Recently, pest risk assessments have begun to consider potential expansions of species' geographic distributions and plant host ranges based on predictions of future climates and land uses. These assessments will become more sophisticated with improvements in modelling tools, climate forecasts (including extreme events), and plant distributions (cultivated and non-cultivated hosts), and greater knowledge of factors that determine invasion success.
- **Better knowledge of species arriving at New Zealand borders.** To accurately profile biosecurity hazards, greater understanding is needed of why some species establish in New Zealand despite having never been intercepted, and why some frequently intercepted species have not yet established. Fundamental to this is access to better interception data across all pathways, including surveys to establish contamination rates, species identifications, and other information such as country of origin, and the condition and physiological state of the intercepted organisms.
- **Methods for comprehensively analysing risks to all societal values.** New hazards seem to be emerging at a faster rate, and the distributions of some pests have rapidly increased with unexpected impacts on agricultural, urban and natural ecosystems. Range expansions of certain

cultivated plants also affect the ability of pests to establish in new areas (see below "Vulnerability of host plants and ecosystems"). New Zealand's Biological Heritage National Science Challenge is developing a risk assessment framework that emphasises social, cultural, and environmental considerations.  More comprehensive pest risk assessment methods are needed that properly consider the full range of potential impacts including the extent to which biosecurity incursions such as myrtle rust, vespid wasps, and polyphagous coccinellids may harm New Zealand's native and valued non-native biodiversity. Potential impacts need to be assessed in the context of already rapidly declining biodiversity (the extinction crisis) and the possibility of cascading effects when multiple biological invaders are introduced (invasion meltdowns).

## Changing pest pressure on the border (Exposure)

Most New Zealand biosecurity risks are managed offshore and at the border through pathway risk management of passengers and cargo. Certain pathways are more tractable for management than others, but a large uncertainty remains around the exact nature and levels of associations between specific pests and the different types of travellers or imported goods. Some pathways are also on the rise, such as e-commerce.

Priorities for further work include:

- **Understanding pathway-pest associations**. To improve risk assessments, it is essential to understand both the pest categories associated with different pathways (see above "Better understanding of the pool of species arriving at New Zealand borders"), and pest arrival rates, invasion histories and the effects of risk mitigations on probabilities of entry and establishment. Drivers of past invasions may also help predict future ones. Factors such as import types, volumes, and sources could be analysed with respect to historical arrivals of different pests (or pest categories) to help predict how future scenarios for trade patterns and other global changes will influence biosecurity pressure. The influence of major events such as environmental catastrophes that caused widescale agricultural losses or trade and travel restrictions (e.g., Covid 19) might also be analysed.
- **Better appreciation of non-commodity related pest arrivals.** Tourists, business travellers, and returning residents have differing levels of biosecurity awareness, and the biosecurity risks they present also vary. Identifying the more at-risk groups and the more likely location for pest entries (different for different categories of international visitors) are important biosecurity activities, and ones which already receive a lot of effort. However, any improvements may benefit risk assessment, border interceptions and surveillance. The benefits of improving travellers' awareness or implementing dedicated mitigation procedures for certain categories of travellers or activities, are also to be evaluated. Like trade pattern analyses, traveller-pest associations, historical relationships and future scenarios could also be analysed with regard to international travel and tourism. At last, undeclared intentional introductions of potentially invasive species remain largely under evaluated. These can be promoted by e-commerce and the development of specific trends for certain exotic plants or arthropod pest species. Other

organisms can be “smuggled” for other reasons, including unofficial biological control, livestock genetic improvement, or improved pollination/primary production.

- **Evaluating climate change effects on natural introduction pathways.** Climate change is affecting the frequency and intensity of storms and altering sea temperatures and currents. These changes will likely influence non-native species’ probabilities of natural dispersal to New Zealand. Atmospheric and sea current modelling could be used more extensively to estimate current and future risk profiles including the most at-risk locations for entries into New Zealand.

## Vulnerability of plants and ecosystems (Vulnerability)

Biosecurity risks to New Zealand’s natural environment are less well understood than risks to its agriculture.

Priorities for future research include:

- **Refining predictions of future land uses.** Such predictions are needed to ensure risk analyses incorporating climate change consider the plants that will become most important to New Zealand in the future. Changes in primary production will be driven primarily by the interplay between economics, climate change and government regulation (e.g., Emission Trading Scheme, water allocation and quality). B3 should forge stronger links with programmes working to predict future New Zealand land uses (e.g., Our Land & Water). Identifying changes in vulnerabilities of native plants is even more problematic and will strongly relate to their specific uses and growing environments (e.g., specialised crops, urban plantings, or natural land).
- **Identified vulnerabilities from overseas experiences.** A comparatively simple method to identify potential pest damage to New Zealand plants is the observation of insect pests, pathogens and weeds associated damage in other countries. Many of the economically valuable, cultivated plants in New Zealand are also valued overseas, thus giving us relatively abundant pest damage records under different growing conditions and early indications of their vulnerability. However, there are exceptions with both non-native (for instance few countries other than NZ regard white clover as economically prominent) and native crops (for instance manuka to support honey production). Specifically investigating these less common plants or crops could prove valuable (e.g., records of pest damage on *Leptospermum*/*Kunzea* in Australia). Although there has been considerable effort in this area to date, real-world implementation has proved problematic. Damage on many New Zealand native plants can be more difficult to collect from overseas. Information on species that are not used as crop or ornamental species can be documented from existing botanical gardens and arboreta, or in specific locations planted for this purpose (“ex-patria” or “sentinel” plantings). Surveys and identification of novel host associations with pests in these settings provide information about the potential impact of these organisms in other countries. Better documenting the role of growing conditions and meteorological factors on pest impacts in non-NZ locations can support better projections for potential regional impacts in New Zealand. Similarly, investigating locations that are the most similar to those under different New Zealand climate change scenarios can provide more useful projections of impacts in our future environments.

- **Understanding host plant climate stressors and interactions with pest vulnerability.** Complex plant-climate interactions are still not fully understood and render current predictions for certain agricultural sectors difficult (e.g., plant growth may be reduced during drier periods of the year but compensated due to the beneficial effects of $CO_2$ increase in other periods). These interactions are even more complicated in other natural and urban environments, which are much more complex ecosystems and where plant responses involve multiple interactions at different trophic levels, including with competitors and natural enemies. For instance, plant responses to elevated $CO_2$ are not well understood, especially in their response to pest attacks and disease. Biosecurity risk analysis might benefit from better understanding of the complex interactions of $CO_2$ increase with factors such as water availability and temperature, however this knowledge is arguably more likely to benefit post-border pest management. Secondary insects and weak pathogens might become more damaging in areas where hosts become more suitable, and/or natural competitors and enemies are lacking. While there has been considerable interest in "tipping points" (van Nes et al., 2016) and "invasional meltdown" (Simberloff, 2006; Simberloff & Von Holle, 1999), the ecological truth of these concepts is still under debate. A better understanding of association mechanisms and interactions between plants, pathogens, and biotic vectors (usually insect) is needed to identify whether such scenarios might arise through pest and pathogen invasions. Some of the effects of land cover changes in the natural environments, such as in locations invaded by wildings, or where treelines are displaced, are also poorly known and would provide insightful indications of the future effects of climate change.
- **Addressing the role of urban areas as bridgeheads for biological invasions.** Many invasive species are first introduced in urban locations. These provide the new invaders with a range of habitats (more or less disturbed), potential hosts (of varying health conditions), and microclimates. Altogether these heterogeneous conditions can be more favourable for the early establishment of a wider range of pests and pathogenic organisms than any other type of environment. Furthermore, urban systems provide more opportunities for newly introduced species being vectored towards both near and distant areas through human means of transportation. Urban areas are extremely diverse and heavily fragmented landscapes, but their vulnerability and permeability to invasive pests, pathogens and weeds remain poorly studied. This is an important area of research that should be addressed in a context of ever-increasing urbanisation, notably addressing the spatial distribution and composition of exotic and native plants that can be used as hosts for invasive species. Interfaces between cities and productive and natural lands, and new suburban areas in particular, may play a key role in invasive species expansions.

## Evolving biosecurity management tools and constraints

Although not formally considered as a fourth component in B3's scope of work, biosecurity management tools and constraints will undergo significant changes. We can be able to prevent pest introduction more efficiently with the help of new tools and technologies. Alternatively, there are also global or national evolutions and disruptions that may affect the ability for biosecurity practitioners to prevent new species arrivals or establishments.

Priorities for future research include:

- **More rigorous collection of pest contamination data across different pathways.** Pests moving globally in association with traded commodities or travellers need to be identified and managed, ideally before they escape in the New Zealand environment. Border inspection and records of intercepted organisms plays a crucial role in plant biosecurity programs, but these data are difficult, expensive, and in some cases probably illegal to collect. In particular, the origins of pathway materials is often known at only a very coarse scale, and in the case of hitchhiker pests it may not be obvious where along the pathway that contamination may have occurred. It probably is possible to improve the collection and analysis of some pathway data, but alternative means of monitoring pathway risks might also be investigated. For example, tracking the origins and capturing other biosecurity relevant information for shipping containers and critical import vessels (e.g., ships) or goods (e.g., used vehicles) could be facilitated by the development of new technologies (e.g., remote sensing) and shared databases. Similarly, systems could be put in place to better track the origins, points of destination and other biosecurity relevant information for international travellers.
- **Improved phytosanitary treatments and other pest risk reductions options.** Some of the obvious management options currently available, such as insecticides, may not be in the future. The need for alternatives to environmentally unsafe or socially unacceptable solutions will also drive new, “greener”, solutions for pest management. Pesticide resistance, or more generally uncertainty around efficacy of pesticides and other treatments, will also push future adoption of systems approaches, but their efficacy and applicability need to be assessed. Certain solutions may also need to be evaluated with regards to their impact on greenhouse gases emission (e.g., pesticide production), or other risks compromising their use (e.g., supply chain issues).
- **Options for early detection and monitoring**. Rapid technological evolutions provide the potential for improved surveillance tools on pathways and at the border. Solutions based on imagery and automated recognition of biosecurity issues may drive development and adoption of future tools, including the ability to recognise pests directly (e.g., camera traps and other image-based sensors to detect pest contaminants) or indirectly through the identification of at-risk material or host plants (e.g., sensors for soil contaminants or debris, identification of hosts and their condition through ground or aerial images). Other prospects are based on volatile or sound detection, which could be applied all along the supply chain, from the places of exports to arrival locations in New Zealand.
- **The utilisation of shared databases and information platforms**. Awareness of current and “emerging” pests of concern is essential to New Zealand. Shared international resources provide access to an ever-increasing number of scientific publications and grey literature. The development of e-mail communication, videoconferencing and other networks are also providing more opportunities for networking and the ability to reach out to a wide range of national and international subject matter experts. However, the IPCC still recognises that biosecurity information-exchange activities generally remains of a passive nature. This, in combination with limited knowledge of pest behaviour under new climatic and ecosystem conditions, can result in a deficiency of reliable, scientifically verifiable information upon which

risk assessors and regulators can frame their assessments and mitigation measures in a global change context. At NZ level, a large amount of information pertaining to biosecurity is still scattered across different organisations (MPI, industry, research organisations). Centralising information and reports together, such as interception data, NZ and overseas establishments and response plans, host plants and impacts, including from projects that never get published or collated, can only be beneficial to our biosecurity system. The shaping of a NZ biosecurity dashboard would need to be discussed between the main actors in the biosecurity system, especially MPI. Common frameworks addressing current and emerging risks is essential in that respect, notably for the identification of pest species and/or functional groups (to account for unrecognised species) that could arrive, evade our border biosecurity processes and establish in NZ under current and future conditions. Developing a greater diversity of information sources and networks is also required, especially to include non-English information from Asia, South America, Africa, or Europe.

## The potential impact of invasive species as global or regional disruptors

Our review considered the impacts that numerous drivers of global change could have on biosecurity (Section 1), but current biosecurity actions may also feed back into these megatrends. Pesticides, fertilisers, irrigation, and other pest management tactics have large economic and environmental costs, affecting the profitability, sustainability, and market appeal of its primary products. Agrochemical production and use also contributes to greenhouse gas emissions (Heimpel et al., 2013). In New Zealand, when asked how to reduce their greenhouse gas emissions, farmers identified a range of possible actions including a better use of fertilisers and avoiding the use of other chemicals (MPI, 2019). However, it remains uncertain how they may be able to do this if no alternatives are provided to them for pest control, and without affecting their sustainability. Alternatively, if pest impacts remain unmanaged, the economic, societal, and environmental costs can be even higher.

The InvaCost initiative has provided a global synthesis of the monetary costs of biological invasions worldwide, estimating the total reported costs of invasions reached a minimum of US$1.288 trillion over the past few decades (1970–2017) (Diagne et al., 2021). The reported economic damages caused by invaders were approximately an order of magnitude higher than the money spent for management. In New Zealand, minimum costs of current pasture pests and productive sector weeds are estimated to be comparable to the eventual maximum GDP costs of climate change (Figure 4). While these data are imperfect, they do indicate the relative importance of biosecurity relative to climate change in New Zealand’s economy.

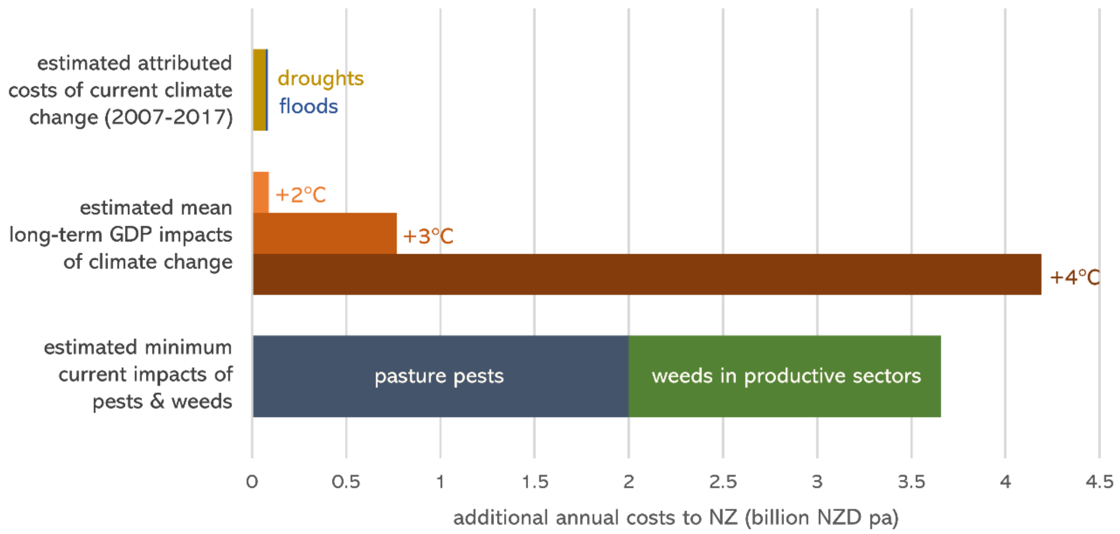


**Figure 4**. Estimated costs to New Zealand of climate change (top: current additional droughts and floods (Frame et al., 2020); centre: GDP impacts under different warming scenarios (Kompas et al., 2018) compared to current pasture pests (Ferguson et al., 2019) and productive sector weeds (Saunders et al., 2017).

There are multiple examples of pest and disease outbreaks that have amplified climate change such as xxx. For example, damage from forest pests in the United States releases $CO_2$ at rate in the same order of magnitude as wildfires (Kurz et al., 2008). Tree-killing epidemics have potential to transform forests from carbon sinks to carbon sources. Mitigating climate change by planting trees is widely recognised, but new plantings might not keep up with the loss of biomass associated with pest damage from a major new pest of indigenous or exotic forest. Although invasive species issues are well documented in the IPCC report on Climate Change Impacts, Adaptation and Vulnerability (IPCC, 2022a), risks associated with pest damage were not considered in the associated report on Mitigation options (IPCC, 2022b).

## Key messages

- New Zealand biosecurity stakeholders are most concerned about future trade patterns, general climate warming, population mobility, and agricultural intensification. Other trends of secondary concern include eCommerce, biodiversity loss, changes in sea and air currents, human population growth, rainfall patterns, and weather extremes. However, the survey sample size was small, and Māori were under-represented in the survey.
- We propose border biosecurity research, capability and investment priorities in the context of global change to be supported in the following areas: (A) developing better methods to recognise functional groups and pest species that could arrive, evade our border biosecurity processes and establish in NZ under current and future conditions (=map and prioritise the range of pest hazards); (B) developing new methods and tools to evaluate when and where

our borders are experiencing changes in pest pressures, and when possible forecast these changes, including possible adaptations in our biosecurity responses (=quantify current and future pest pressures); and (C) evaluating the vulnerability of our host plants and ecosystems, including possible evolutions of these systems under land use or climate change (= assess the range of environmental vulnerabilities and quantify these).

- Should any new significant biological invasion in NZ or elsewhere result in significant impact to primary production systems or environment, this could also lead to major regional or global disruptions that can in turn potentially amplify climate change (e.g., given an increased for chemical treatments, long-distance food and products transportation, or a reduced ability to mitigate greenhouse gas emissions).

# Section 6. Discussion and recommendations

## General discussion

Climate change and other global trends will influence the nature of New Zealand's future biosecurity risk by pressuring agricultural and other environments in new ways, shifting global patterns of pest movement by trade and natural dispersal, and altering the environmental and biotic conditions affecting pest and pathogen establishment and impacts.

This report reviewed more than 30 global megatrends and assessed the range of potential direct and indirect impacts they could have on New Zealand and its biosecurity. The trends will interact in complex ways, which means accurately predicting their influences on New Zealand biosecurity will not be possible. For example, recent unanticipated events unrelated to climate change, such as the Suez Canal blockage, the Russia/Ukraine war, and the COVID-19 pandemic, quickly impacted global production and supply chains. These have all affected international pest and pathogen movement in different ways, and the Ukraine War will have significant ongoing implications for climate change itself. Because such events are not easy to predict we cannot make specific preparations for them. Instead, we must ensure that border biosecurity systems are sufficiently robust and adaptable to provide protection from exotic pests and disease invasions despite a range of external shocks. Biosecurity research should focus on general solutions rather than on specific global trends such as climate change.

Biosecurity risk can be conceptualised as the intersection between hazards (the huge pool of exotic pests and pathogens that might invade New Zealand), exposure (the pathways and processes of entry, establishment and spread) and vulnerability (how invaders may impact on the ecosystems and values that we care about). The challenge of **hazards** is intimately tied to the problem of identifying and understanding global biodiversity. Molecular methods are facilitating the cataloguing of species but morphological taxonomy is lagging behind. Beyond a name, we know next to nothing about the ecology of most species, including some of those identified as major biosecurity threats. Without taxonomic completeness biosecurity decisions can still be framed around functional groups and the traits of invaders, though this more difficult under international trade law. Identification of species traits that correlate with biosecurity risk is a priority for further research.

Robust hazard assessment will rely on the sharing of international knowledge through databases and reliable literature, including different languages and overseas indigenous knowledge. As the volume of accessible data increases, we will need more efficient and effective ways to process it, screening to identify the most significant biosecurity hazards. These systems should recognise and accommodate global change, such as shifting climates and the resulting realignment of species distributions. In addition, we need tools to rapidly detect, characterise and report the threats posed by the emergence of whole new taxa, especially pathogens. The capability and technology need here are primarily around data collection, processing, analysis and interpretation.

New Zealand's geographical isolation means that **exposure** pathways are relatively well characterised and managed. The global trends discussed in Section 1 are unlikely to change the types of entry pathways but will instead have major impacts on their relative importance and therefore on the optimal deployment of pathway management resources. For example, the COVID-19 lockdowns caused a huge increase in e-commerce and a surge in the volume and biosecurity risk associated with international mail and courier pathways, while at the same time international air passenger pathways shrank dramatically. Over longer time frames, climate change may alter the supply and demand of agricultural commodities, affecting trade pathways. The COVID-19 experience demonstrated that MPI was sufficiently agile to re-deploy staff across shifting pathways, but equipment and infrastructure are less mobile. Therefore, it would be useful to be able to forecast and prepare for changes in pathway pressures rather than simply react. Robust methods are also needed to quantify and monitor pathway contamination, and to verify that treatments have been applied. There is also a role for new methods, such as remote sensing, for identifying, tracking, and monitoring border pressures. New technologies for treating or intercepting risk organisms are needed, especially if climate change, trade shifts and overseas spread change the profile of pest organisms that need managing on import pathways.

Biosecurity threat exposure is not just about the pathways of entry, but also includes pest establishment and spread, as well as the biosecurity actions that aim to minimise this: post-border surveillance, response, and eradication. The process of establishment is likely to be affected by global trends such as climate change and urbanisation. However, random chance plays such a strong role that it may not be possible to manage establishment in any meaningful way outside of minimising founder population size and frequency through effective pathway interventions.

The ability to detect, respond and eradicate incipient pest populations relies on social license, which may be affected by several of the societal factors discussed in Section 1 as well as one that has increased noticeably since we started compiling this review: mis/dis-information. The social license to conduct post-border biosecurity and pest management may be threatened unless biosecurity authorities can effectively communicate the risks and benefits to an increasingly distrustful public. Here is a role for the social sciences to better understand and advise, especially as biosecurity may be seen as less important compared to very visible threats like climate change, international conflict and pandemics.

The **vulnerability** of current and future landscapes to exotic pest impacts is well characterised for productive sectors but poorly understood in the case of native ecosystems. Furthermore, we currently lack tools to evaluate impacts on non-economic values, including environmental, socio-cultural and te ao Māori values. In some areas, even the economic impacts may be incomplete, as in the effects of incursion responses on value chains and local transportation networks. Some work is underway in New Zealand's Biological Heritage National Science Challenge, but much other work is or could be relevant to these issues.

A key challenge in all of this is uncertainty. Border biosecurity is inherently stochastic, involving unlikely events that potentially have very large consequences. But that does not mean that progress is not possible – indeed the huge number of threats means that pests and pathogens are constantly pressuring New Zealand's border systems

Finally, it is worth emphasising that New Zealand's experience of global issues such as climate change and new pests will differ from other parts of the world, so we cannot look to overseas research for all the answers. New Zealand's unique situation, economy, culture, natural ecosystems, existing pest pressures and border biosecurity systems mean that much of the knowledge we need must be sourced from within. There is an opportunity for the New Zealand Government, CRIs and biosecurity partner organisations (like B3) to better prepare for the future and enhance coordination, analytical capacity, and communication around global change research relevant to border biosecurity.

## Specific recommendations for B3

The biosecurity implications of global megatrends, including climate change, are both wide and diffuse. Many will require cross-sector and cross-disciplinary research to address, and B3 is ideally situated to contribute in this way. However, many of the issues transcend B3's current scope (plant border biosecurity), making it difficult for B3 to lead research in these spaces (e.g., end-to-end pest management, "One Biosecurity", farm systems change, interactions between environmental change and environmental pests). B3 can, however, contribute to such work, and should seek out partners and independent funding to engage in broader scale research relevant to global change.

A few specific areas appropriate for B3-funded research have been identified, most of which are already being advanced. These include developing and improving trait-based approaches to risk assessment, new methods to forecast, track and monitor changing border pressures, and better understanding potential impacts of pests and pathogens on a wide range of economic, environmental, socio-cultural and te ao Māori values. However, the most appropriate response from B3 to global change is to help ensure that New Zealand's border biosecurity systems are sufficiently robust, resilient, and adaptable to remain effective during the challenges ahead. No fundamental change is needed in our biosecurity systems, just ongoing improvement. This is where B3 plays a key role, with research that may not specifically target global change, but which will nonetheless be relevant and impactful.

However, B3's contributions to addressing global change issues could be more coordinated and visible. For example, it may be useful for a member of the B3 Theme Leaders Group to take responsibility for oversight of climate change relevant research across the whole B3 portfolio. The aim would be to first identify which of B3's projects are relevant to climate change, then ensure coordination and sharing of data and resources between the projects and teams. Researchers should be encouraged to use and contribute to shared data sources (including international databases) and to present their biosecurity work at climate change themed fora. The coordinator might also work with B3's Communications Support to target climate change relevant publications. And the coordinator should also look out for opportunities for B3 to collaborate with research going on outside B3, where it includes B3's scope.

Data access and sharing is a key requirement for effective and robust biosecurity systems. MPI and others continue to struggle with multiple incompatible and fragmented databases making data access and use very challenging. B3 has similar issues with orphaned databases and cases of poorly documented other information. New decentralised methods are now available for storing and managing access to data, so there is an opportunity for B3 and others to make the hard-earned experiences of the past more available for tackling the global change challenges of the future.

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