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Manatū Ahu Matua

Review of the impacts of climate change on soil processes and the consequences for ecosystem services

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Preface

The Ministry for Primary Industries (MPI) Sustainable Land Management and Climate Change (SLMACC) programme provides funding for research to understand the impacts of a changing global climate. The programme described in this report is part of the SLMACC investment priorities for 2012/13 that deals with the impacts of climate change on soil services, soil carbon and soil nitrogen cycling. A team of people from the four Crown Research Institutes (CRIs) that comprise the Soil Land Use Alliance[1] (SLUA) was assembled along with staff from another CRI (NIWA) to produce a multi-CRI review to synthesise the evidence for climate change impacts on soil services, soil carbon processes and stocks and soil nitrogen cycling under farming and forestry systems. This multi-CRI review is a link of three contracts with MPI under the SLMACC programme: LCR30796 for soil services (Landcare Research led), FRI30559 for soil carbon processes and stocks (Scion led), AGR30693 for soil nitrogen cycling (AgResearch led). This project provides a comprehensive review of key international and national documents, reports, and published peer-reviewed literature, as well as identifying gaps in the current knowledge base. A key component of the review process was a national workshop that involved experts in a facilitated discussion to ensure the review captured the latest thinking in relation to climate change impacts on soil services, soil carbon and soil nitrogen cycling.

1) *The Soil and Land Use Alliance (SLUA) is a collaboration among AgResearch, Landcare Research, Scion, and Plant & Food Research that stems from their shared purpose in enhancing New Zealand's soil and land resources through sustainable management. The collaboration recognises that the best outcomes for New Zealand will result from co-ordinated investments, research activities and capability development across the range of landscapes, sectors and land uses that the SLUA member organisations represent. The priority for SLUA is to deliver research that contributes to economic growth for New Zealand, essentially contributing to a green growth agenda, in close collaboration with our stakeholders.*

This report identifies those impacts on soil ecosystem services (resulting from climate change to soil natural capital stocks and soil processes) that will be the most significant for New Zealand's primary land-based productive sector by 2049 and beyond.

Key messages

Net production from New Zealand's primary land-based productive sectors could increase under a changing climate. However, climate change may also negatively affect the ability of soil to regulate water and erosion, nutrients and pests. If the regulating services provided by soil are not carefully monitored, the negative effects on these services could offset any gains in production.

Climate change in New Zealand

Projected changes to New Zealand's climate include higher atmospheric carbon dioxide concentrations, higher temperatures, wetter western regions, drier eastern regions, and more extreme weather events by 2049 and 2099. Together, these changes will lead to a more variable and extreme climate that will have both positive and negative impacts on primary land-based sectors.

Impact on ecosystem services

Soil processes, in particular those that affect carbon and nitrogen cycling, are important both to provisioning ecosystem services (production of food and fibre) and regulating services (regulation of water, nutrients and pests) provided by soil. The increase in net primary production could be a positive benefit from climate change if it results in greater yields of desirable products. However, more droughts/storms and weaker regulation of water, nutrients and pests by soil have the potential to counter increases in net primary production. Direct costs incurred by loss of regulating services include damage caused by floods/erosion and loss of yield from drought or soil-borne pests and diseases. Indirect costs include compensation to avoid loss of provisioning services such as increased fertiliser use, pesticide use, or erosion mitigation measures.

Impact on soil natural capital and processes

Soil is a dynamic system composed of physical, chemical and biotic components (soil natural capital stocks) that comprise our landscapes and productive sectors. Soil natural capital stocks are influenced by soil supporting and degrading processes, which together form soil infrastructure and provide the services humans obtain from soil.

Climate change will affect soil through accelerated nutrient cycling, possible loss of soil carbon, and more frequent extreme events (such as drought or heavy rain that leads to erosion). Extreme events will affect all primary land-based sectors. Soilborne organisms that cause disease or are considered pests are likely to increase because of warmer temperatures and greater plant stress caused by increased drought and/or intense rainfall. The impacts are generally expected to be lower in the cropping and intensive pastoral sectors as these are more highly managed than the extensive pastoral and forestry sectors.

Soil carbon and nitrogen are closely linked; both cycle through the soil and associated biotic systems. The processes that contribute to carbon and nitrogen cycling are negatively affected by external soil-degradation processes, such as erosion. Plants take up nitrogen, removing it from the soil so productivity may be reduced if the availability of nitrogen and other nutrients (particularly phosphorus) is limited. When nutrients (and water) are not limited, the net primary production of plants is expected to increase as a result of warmer temperatures and higher levels of carbon dioxide. Little is known about how climate change will affect the soil biota that control carbon and nitrogen cycling processes and this lack of information is one of the largest knowledge gaps in predicting the impacts of climate change on soil.

Impact on land management

Land management practices are likely to alter in response to climate change. Changes will be aimed at avoiding limitations of nutrients and water and maximising any increase in the net primary production of plants as a result of warmer temperatures and more carbon dioxide. While the main focus of this report is to discuss climate change impacts on soil processes, natural capital and regulating services, it is also appropriate to provide comments on potential changes to land management practices in response to climate change. Indeed, changes in land management are likely to have a greater impact on soil natural capital than changes in climate. Using the best possible management practices and new technologies could enhance net primary production but they may have further negative consequence for regulating services if not carefully implemented.

Knowledge gaps and recommendations

Accurately predicting the possible impacts of climate-change on soil systems is difficult. Reasons for this include the inherent complexity of soil systems, the variable effects of climate change in different areas of New Zealand, and a lack of knowledge on key aspects of soil systems.

More information is required on how:

- *Interactions between increased levels of carbon dioxide, increased temperature and changes in rainfall will affect soil regulating services* (to obtain a better understanding of the complexity of impacts at a farm-system scale).
- *Soil biota respond to both direct and indirect climate variables* (to improve projections on carbon and nitrogen cycling processes).
- *To develop more reliable models* of carbon and other natural capital stocks (to project changes in soil natural capital across New Zealand at a regional/national scale as well as on a farm/paddock scale).
- *To develop improved indicators* (to measure ecosystem services and to improve the projection of climate-change impacts on soil services).
- *To establish base-line levels of soil natural capital* (to allow for an assessment of land management responses to climate change).

Introduction

New Zealand's climate is changing and will continue to change. It will also become more varied and more variable. Under a changing climate, soil processes that support New Zealand's primary land based productive sectors are expected to be impacted upon. These primary land-based sectors are a mainstay of New Zealand's economy. For example, agriculture is expected to have export revenues in 2013 of $21.1 billion and forestry $4.5 billion [1]. Uncertainty associated with the impacts of climate change on soil and the ecosystem services they provide (including food and timber production), is one of the biggest threats to mankind globally.

Soil is a critical, but often overlooked, component of New Zealand's land-based productive sectors. New Zealand's soil types are diverse due to a large range of parent materials. The majority of soil types under the productive sectors are mineral soils. In general, North Island soil types are influenced by volcanic deposits and South Island soil types are from river, wind and glacial deposits. Soil temperature, moisture content and nutrient levels are all affected by climate and will be impacted by climate change. It is critical for New Zealand's economic future to understand how climate change will affect soil, as changes in soil properties will impact on the productivity of the land.

Recent European research has focused largely on the impact of climate change on soil carbon content rather than on soil ecosystem services or soil nitrogen cycling [2]. Key findings from that work indicate that, although climate change will impact on soil carbon in the longer term, it will have less of an impact than changes in land use and management. Because soil management has a significant impact on soil carbon, adequate management could mitigate the impacts of climate change.

This stakeholder report assesses the possible effects of a changing climate on New Zealand's soil and land-based sectors. It also highlights what future research is needed to inform gaps in current knowledge. This report addresses the question: "how might climate change impact on New Zealand's soil resources and what are the consequences for land-based sectors?"

Methodology

Information on the impacts of climate change on soil services, soil carbon processes and stocks and soil nitrogen cycling was collected by reviewing published and unpublished national and international literature. This information was presented at a national workshop held in Wellington, New Zealand during February 2013. Participants included New Zealand's leading soil scientists as well as climate experts from NIWA and key staff from MPI (a list of participants is provided in Appendix 2). The workshop group investigated and debated the available evidence regarding climate change on soil and also identified key knowledge gaps that need to be addressed in order to provide more certainty around the outcomes. All the information obtained was collected and integrated into a detailed technical report (Appendix 1). Further synthesis and evaluation were undertaken to generate this stakeholder report. This process is illustrated in Figure 1.

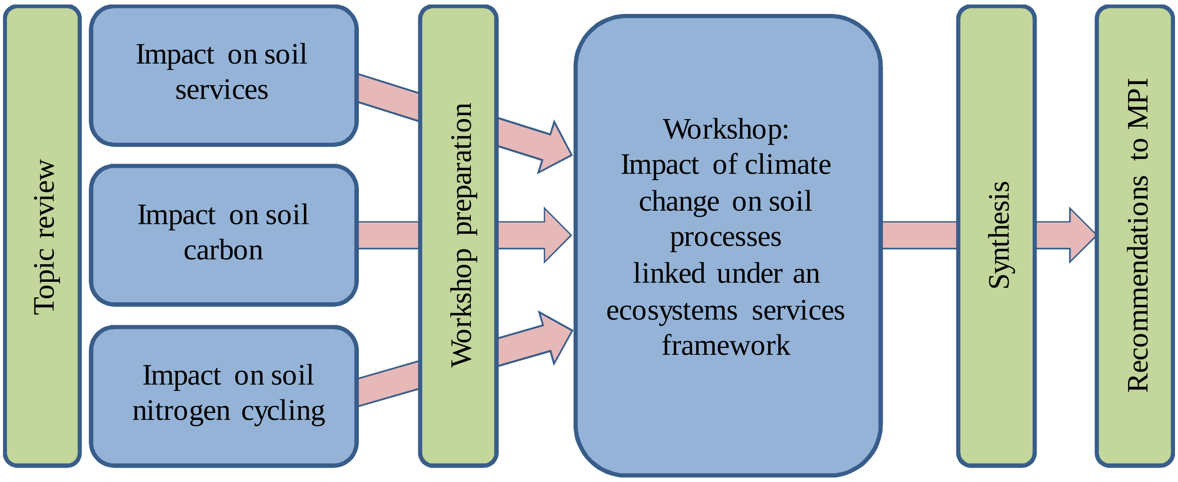

Figure 1: Process used to assess the possible effects of a changing climate on New Zealand's soil and land-based sectors.

CLIMATE CHANGE IN NEW ZEALAND

Future changes in the climate are not known with certainty. Projected changes in climate are dependent on the assumptions made about the impact of greenhouse gases. It is important to examine different scenarios for their likely impacts on soil processes. Two scenarios, "high carbon" and "rapidly decarbonising", were selected for this study. They represent the likely extremes of future emissions and global climate changes for the periods 2030-2049 and 2080-2099. Global average temperatures would be about 4 °C above pre-industrial levels by 2099 under the "high carbon" scenario but only 2 °C higher under the "rapidly decarbonising" world scenario. Other predicted changes include an increase in carbon dioxide concentration, changes in rainfall timing and severity, and a greater frequency of extreme events (number of hot days above 25 ^{o}C, droughts, and strong winds), Table 2.

HOW THIS REPORT WORKS

This review addresses each of the following key questions in a separate section:

- **Natural capital and ecosystem services of soil** – *What are they and why are they important?*
- **Impact of climate change on soil ecosystem services** - *What are the resulting impacts of climate change on regulating and provisioning services, and will these impacts vary among the different primary sector land uses (pastoral, cropping, horticulture, forestry)?*
- **Impact of climate change on New Zealand soil natural capital stocks and processes -** *how might climate change be expected to impact on soil natural capital, soil process and how they link to regulating and provisioning services important to New Zealand's primary land based productive sectors?'*
- **Impact on land management** – *How will land management be impacted by climate change?*
- **Recommendations for future research –** *What are the recommendations for future research to ensure the prosperity of soil services in New Zealand's primary land based productive sectors under a changing climate?*

Table 2: Predicted ranges for key climate variables based on diverging scenarios of carbon dioxide increase [(1)]. The range in values provided a guide for magnitude of climate change effects we assess in the report. Changes are relative to 1980-1999 levels.

Variable	Season	Region of NZ	Range predicted for year 2049	Range predicted for year 2099	Level of confidence in predicted values
Carbon dioxide * (ppm)	All	All	480 to 530 ppm	450 to 850 ppm	Moderate to high
Temperature (°C)	All	All	0.7 to 0.9	1.1 to 2.6	High
Change in rainfall (%)	Summer & Autumn	South & west S.Is. Rest of NZ.	Zero to +5% Up to ±5%	Zero to +5% Up to ±5%, & >+5% in eastern Nth Island	Moderate
	Winter & Spring	North & east N.Is., Marlborough, Canterbury Plains West N.Is., south & west S.Is.	Zero to -10% Zero to +10%	-5 to -20% Zero to +30%	High
Hot Days	Summer half-year	All lowland areas	Up to 100% increase	Up to 300% increase	High
Frosts	Winter half-year	Central N.Is. & S.Is.	Up to 50% reduction	Up to 50-90% reduction	High
Heavy rainfall	All	Especially in west of both Islands & south of S.Is.	Extremes occur up to 50% as often	Extremes occur up to 100% (i.e. 2 times) as often	High
Drought	Summer half-year	Mainly eastern areas Eastern S. Is. & all of N. Is.	Up to 5-10% more of year	At least 10% more of year	Moderate for type of change; low for magnitude
Strong winds	Winter, Spring Summer/ Autumn	All N. Is. S. Is.	Increase of few % Little change Decrease of few %	Increase up to ~10% in frequency Little change Decrease of few per cent	Moderate for type of change; low for magnitude

[(1)] From the “high carbon” and the “rapidly decarbonising” world scenarios
* Current level of carbon dioxide is 395 ppm

Ecosystem services and soil natural capital

'What are they and why are they important?

Soil has an inherent value in providing services to humans. The ecosystem services model provides a framework for valuing soil services [3]. Provisioning services are defined as the products obtained from soil (food and fibre) while regulating services enable humans to live in a stable, healthy and resilient environment (Table 1). This report focuses on how climate change will impact upon soil infrastructure [4] (the soil properties and processes that contribute to natural capital stocks) that provides both **provisioning** and **regulating** services.

Provisioning services are usually associated with commodities in existing markets, so their value is readily apparent. Regulating services are often more difficult to put a monetary value on and are often overlooked in decision making. However, costs can occur if these services are compromised. Direct costs include damage caused by floods and erosion or loss of yield from drought or pests. Indirect costs include compensation to avoid loss of provisioning services, such as increased fertiliser use. Although cultural services are out of the scope of the review, they should be considered when taking ecosystem services as a whole into account.

Table 1: Provisioning and regulating ecosystem services provided by soil [5]. Key services addressed in this report are shown in bold.

Type of Service	Service delivered	Description
Provisioning services	**Provision of food, wood and fibre and products**	Soil physically supports plants and supplies them with nutrients and water. A wide range of plants are grown by humans and harvested for a variety of purposes.
	Provision of raw materials[1]	Soil can be source of raw materials such as peat and clay.
	Provision of support for human infrastructure and animals.	Soil represents the physical base on which human infrastructures and animals stand.
Regulating services	**Flood mitigation**[2]	Soil has the capacity to store and retain water, thereby mitigating flooding.
	Nutrient and contaminant filtration	Soil can absorb and retain nutrients and contaminants, which prevents them from being released into water bodies.
	Carbon storage and greenhouse gases regulation	Soil can store carbon and regulate the production of greenhouse gases.
	Detoxification and the recycling of wastes	Harmful compounds can be physically absorbed by soil or destroyed by organisms that exist in soil. These organisms also degrade dead organic matter, which improves soil structure and releases nutrients.
	Regulation of pest and disease populations	The nature of the habitat provided by soil controls the proliferation of pests (crops, animals or humans) and harmful disease vectors (viruses, bacteria), and regulates populations of beneficial species.

[1] Largely not applicable to New Zealand's cropping, pastoral and forestry primary sectors.
[2] The ability of soil to mitigate flooding is also linked to erosion mitigation and soil-moisture supply.

Soil natural capital stocks are the physical, chemical and biological properties that make up New Zealand's landscapes and productive sectors. Some properties can be managed, such as altering levels of nutrients by adding fertiliser. Soils are also dynamic systems with various degradation and supporting processes occurring continuously. These processes along with natural capital form the ecological infrastructure of soil (Figure 2). The relationships between soil natural capital and the flow of ecosystem services are dependent on the complex interaction between natural capital stocks and soil processes. Behind each service, a number of soil natural capital stocks can be regulated by multiple soil processes and each soil process may, in turn, contribute to several stocks and services [6].

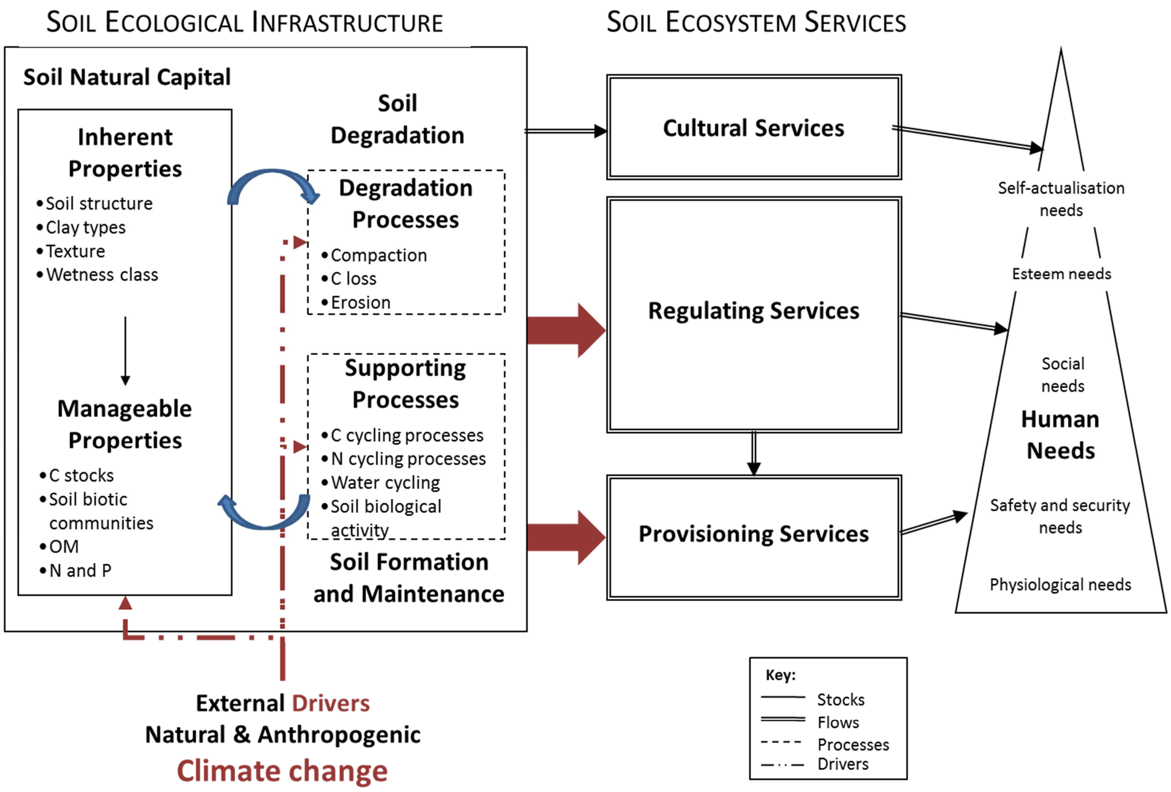

Figure 2: Conceptual diagram of relationship between climate change drivers, soil natural capital, soil processes and ecosystem services (adapted from Dominati et al. [5]).

Climate change will alter the balance between the supporting and degrading processes occurring in soil so will lead to changes in soil natural capital. This, in turn, will impact on the ecosystem services provided by the soil. The approach taken in this review focuses on the mechanisms underlying the provision of services that will be affected by climate change. The delivery of soil regulating services and the vulnerability of the provisioning services to climate change are assessed by considering the underlying soil natural capital stocks and processes.

Impact of climate change on soil ecosystem services

What are the resulting impacts of climate change on regulating and provisioning services, and will these impacts vary among the different primary sector land uses (pastoral, cropping, horticulture, forestry)?

The flow of regulating and provisioning services is derived from the soil ecological infrastructure (which encompasses both soil natural capital and processes, Figure 2). The supporting carbon and nitrogen cycling processes (which are closely linked) are important as they impact other natural capital stocks and processes. Soil degradation processes, such as erosion, reduce the ability of carbon and nitrogen cycling to support soil natural capital. This Section summarises the impacts of climate change on regulating and provisioning services.

REGULATING SERVICES

Regulation of flood and erosion

Soil natural capital includes the capacity to buffer, store and retain water, thereby mitigating flooding and erosion. Under a changing climate, the capacity of soil to regulate floods and erosion will be determined by physical natural capital, which is largely determined by inherent soil properties such as texture, depth, and structure. Soil structure is influenced by manageable soil properties, such as soil carbon content, and soil biota. For example, soil carbon stocks may decline in some situations and/or there may be an increase in dry conditions that negatively impact on soil biota leading to an increase in soil water repellency (or hydrophobicity). These changes will limit the capacity of soil natural capital to mitigate floods and erosion.

Soil water regulation for plant growth will also be impacted by changes to soil structure and therefore, closely linked to regulation of floods and erosion. A decrease in soil structure will negatively impact on soil water regulation.

Regulation of nutrient supply

Nutrient regulation for plant growth (particularly for nitrogen and phosphorus) is mediated by the interactions between plant, soil and microbes. Soil moisture is also important and, where it is limiting nutrient supply, will be negatively impacted. The general consensus from the review was that climate change would over all weaken the capacity of soil to regulate nutrient levels. Faster cycling of carbon and nutrients under climate change conditions will increase the availability of nutrients. These could either be taken up by plants or lost through leaching. Greater demand for soil nutrients by plants will have the positive benefit of increasing net primary production but may lead to nutrient deficiencies in the soil over time, known as progressive nitrogen or nutrient limitation. The capacity of soil to store nutrients will be adversely affects by any decline in soil carbon stocks.

The greatest uncertainty lies in the effect of climate change on the interactions among plants, microbes and soil. Plant diversity (and its effects on soil biota) is likely to be an important issue in extensive pasture and possibly even understorey vegetation in forestry but less so in intensive pasture (rye grass/clover) and cropping systems where species composition is more closely controlled.

Regulation of carbon storage and greenhouse gases

Carbon storage

Soil has the capacity to store carbon and to regulate the production of greenhouse gases thus impacting on the extent of climate change. Globally, soil represents a large and extremely important carbon reservoir that is larger than the atmospheric and vegetation carbon reservoirs combined. New Zealand's soil carbon stocks are expected to remain similar or decline under climate change. Even a small loss in soil carbon stocks can result in significant respiration of carbon dioxide to the atmosphere. A consequential increase in carbon dioxide may result in further warming thus reinforcing the climate-change cycle.

Greenhouse gases

Nitrous oxide (N_2O) and methane (CH_4) are both greenhouse gases. Increases in the atmospheric concentrations of these gases can increase the temperature of the Earth, thereby potentially creating a positive feedback loop. Nitrous oxide production is likely to increase as a result of climate change because rising temperatures will increase the rates of nitrification and denitrification, two processes that generate nitrous oxide. Emissions of nitrous oxide will also increase if predicted increases in urine deposition and fertiliser and legume inputs occur. These processes are dealt with more thoroughly in the Section on nitrogen cycling. Increasing temperatures are also likely to stimulate methane emissions through increased rates of microbial metabolic activity by methane producing microbes. However, other microbes consume methane, and it is not known with any certainty what the effect of climate change will be on these microbes. The degree to which the methane consumers counteract increases in methane production will determine the net effect of climate change.

Regulation of pests and disease populations

The regulation of soil-borne pest and disease populations could arguably be one of the most problematic aspects of climate change for New Zealand's production systems as there will likely be an increase in pests and diseases. In general, dry weather favours insect vectors and viruses, while wet weather favours fungi and bacteria. This may lead to changes in the type and predictability of soil pathogen effects.

The range, abundance, fecundity and activity of insects and microbial plant pathogens are predicted to be altered by climate change as well as the effectiveness of biocontrol agents. In particular, warmer temperatures enable organisms to over-winter more frequently and/or incorporate more generations per year resulting in increased abundances and ranges of various pests. Cold soil in winter kills many pathogenic species, so milder winters due to climate change may substantially increase pathogenic loads. Plant and pathogen phenology will both change with increasing temperature so changes in the timing and efficacy of fertilisers and pesticides will need to be considered from a management perspective.

Extreme events are also expected to increase pathogen load due to increased plant stress. The general trend is likely to be a substantial increase in plant disease, but with some variability, as other aspects of climate change may reduce some pests and diseases. For example, drier summers may reduce pathogen abundance.

Invasions of exotic plant species are also more likely to occur due to changing climatic conditions because native plants may become stressed and less competitive. For example, increasing carbon dioxide concentrations are expected to increase productivity of important N-fixing forest shrub weeds such as gorse and broom. This will lead to increased competition during forest establishment, and the need for greater weed control.

Summary of climate change effects on regulating services

Regulating services flowing form soil natural capital are expected to be reduced as a result of climate change, particularly the supply of water and nutrients for vegetation growth. The key climate change related impacts on soil regulating services for New Zealand's cropping, pastoral and forestry sectors are outlined in Table 6.

Table 6: Summary of anticipated climate change related impacts on soil regulating services by sector (in the absence of adaptation).

Regulating Services	Expected relevant impacts by sector Cropping	Pastoral	Forestry
Regulation of flood and erosion[1]	No change or decreased where carbon declines and soil structure is lost Future soil moisture deficits in areas where less rainfall is expected plus more hydrophobicity and/or evapotranspiration Decreased with corresponding increase in hydrophobicity in areas with less rainfall	No change or decreased where carbon declines and soil structure is lost Future soil moisture deficits in areas where less rainfall is expected plus more hydrophobicity and/or evapotranspiration Decreased with corresponding increase in hydrophobicity in areas with less rainfall Decreased with increased likelihood of heavy rainfall events increasing erosion risk (particularly for hill country soil)	No change or decreased due to increased heavy rainfall events increasing erosion risk after harvesting Future soil moisture deficits in areas where less rainfall is expected plus more hydrophobicity and/or evapotranspiration
Regulating Nutrient supply	Decreased and more reliance on fertiliser Potential for more nitrogen loss with increased reliance on fertilisers	Decreased and more reliance on legumes and possibly fertiliser No change to minor loss for extensive pasture from more nitrogen demand in biomass – potential for nitrogen limitation, possible more reliance on legumes and fertiliser Decreased with increasing soil water deficits, however extreme weather events (e.g. drought-breaking rain) may 'reset' some nutrient cycling processes Changes to nitrogen leaching less certain	Decreased and more reliance on legumes and fertiliser No change to minor nitrogen loss from more nitrogen demand in biomass and none or very low nitrogen input into the system – potential for PNL, possible more reliance on fertiliser Decreased where soil water deficits occur
Carbon storage and greenhouse gases regulation	No soil carbon change or decrease due to increased carbon mineralisation Decreased soil carbon with wind erosion – exacerbated by drought events mainly in eastern areas More ammonia and nitrous oxide from increased fertiliser usage and decreased soil structure More gaseous nitrogen loss as soil buffering and filtering capacity decreases	No soil carbon change or decrease possible due to increased carbon mineralisation Decreased with erosion (hill country) – exacerbated by extreme heavy rainfall events More ammonia and nitrous oxide from increased fertiliser usage in intensive pastures	No soil carbon change or decrease due to increased carbon mineralisation Decreased with extreme heavy rainfall events after harvesting More nitrous oxide from increased fertiliser usage Increased through soil stabilisation in erosion-prone areas Reduced carbon dioxide through biomass accumulation
Regulation of pests and disease populations	Decreased as reduced cold winters Decreased for plants under water stress (i.e. more susceptible to disease)	Decreased as reduced cold winters Decreased for plants under water stress (i.e. more susceptible to disease)	Decreased as reduced cold winters Decreased for plants under water stress (i.e. more susceptible to disease)

[1] Linked to water regulation

PROVISIONING SERVICES

The impact of climate change on net primary production across sectors in New Zealand has been discussed by Clark et al. [7]. In summary, the impacts of climate change on NPP are:

- *Cropping:* modelling suggests small yield losses and potential for yield increases, depending on region and crop type. In general, the greatest benefits were to be found in southern regions growing temperate cereals and forage brassicas, while crops such as potatoes and maize showed more variation, with greater frequency of reduced yields due to water stress and shortening growth cycles.
- *Pastoral:* Small increases in pasture production are predicted in the absence of water and nutrient limitations, with temperate species showing larger yield increases than subtropical species. There will be changes in seasonal patterns of growth with increased growth rates during winter and spring due to warmer temperatures. Autumn will be more variable and there will be an earlier onset of summer with more soil water limitations to growth.
- *Forestry:* Productivity responses are generally positive, with an expected modelled national average increase of 19% by 2040 and 37% by 2090 in the absence of water and nutrient limitations. Responses will vary regionally with greater benefits in the south of New Zealand due to larger benefits of the impact of increasing temperature on net primary production.

Provisioning services, particularly net primary production flowing from soil natural capital, are expected to improve with climate change but only where soil water and nutrients are non-limiting. The key climate-change related impacts on soil provisioning services for cropping, pastoral and forestry sectors are outlined in Table 7.

Table 7: Summary of anticipated climate change related impacts on key soil provisioning services by sector (in the absence of adaptation).

Provisioning Services	Expected relevant impacts by sector		
	Cropping	**Pastoral**	**Forestry**
Net primary production	Potential for increases where there are no water or nutrient limitations Decreased with increased wind increasing wind-erosion risk	Potential for increases where there are no water or nutrient limitations Decreased where soil moisture limited and irrigation not possible Decreased with increased heavy rainfall events increasing erosion risk – net primary production reduced 20% on erosion scars Decrease with drought events and resulting soil hydrophobicity	Potential for increases where there are no water or nutrient limitations Decreased where soil moisture limited Decreased with increased heavy rainfall events increasing erosion risk Potential for nitrogen limitation – long-term decrease
Physical support	No change or decreased support where soil physical natural capital negatively impacted	No change or decreased support where soil physical natural capital negatively impacted Decreased with increased heavy rainfall events increasing erosion risk (e.g. loss of support for roads)	No change or decreased with increased heavy rainfall events increasing erosion risk (e.g. loss of support for roads)

A changing climate may increase net primary production when water and nutrients are not limiting, however it may also negatively affect the capacity of soil to regulate water, nutrients and pests

Impacts of climate change on New Zealand soil stocks and processes

'How might climate change be expected to impact on soil natural capital and soil process, and how they link to regulating and provisioning services important to New Zealand's primary land based productive sectors?'

This report focuses mainly on changes to soil natural capital stocks that are manageable (Figure 2) as it is unlikely that most inherent soil properties will change substantially within the next century. One exception is erosion, which has the potential to greatly alter soil properties. Weathering of soil minerals may also increase over time but change in soil mineral composition is not considered a major issue in the timeframe of this report. Soil natural capital is influenced by soil supporting and degradation processes (Figure 2). The carbon and nitrogen cycles within soil greatly influence the availability of nutrients to plants and animals, so are important both to provisioning and regulating ecosystem services. Soil degradation processes, such as erosion, reduce the cycling of carbon and nitrogen so impact on soil natural capital.

SOIL PHYSICAL STOCKS AND PROCESSES

The physical natural capital of soil is the arrangement of solid particles, water and air that comprise soil structure. The mineralogy and particle size distribution of the parent material are major influences on soil structure but other soil properties can modify structure, particularly carbon content and source (Figure 2). The degrees of aeration, water infiltration, nutrient supply and resistance to erosion of a particular soil are determined by its structure and are crucial in sustaining productivity and environmental quality. The interaction of solid particles (soil minerals and organic complexes) with soil water and air also affects soil chemistry.

Physical characteristics and structure

Air temperature and moisture are two of the main abiotic drivers of soil processes. These factors influence soil temperature, water and carbon contents, macroporosity, biological activity, nitrogen mineralisation, and water repellency of soil. So, changes in temperature and rainfall due to climate change will affect the physical natural capital of soil. Many of these effects are interrelated (Figures 3 & 4). For example, a rise in air temperature will lead to warmer soil and increase rates of biological processes. This will impact the carbon content of soil, which in turn will impact soil structure, porosity, nitrogen mineralisation, water content, and water repellency, Figure 3.

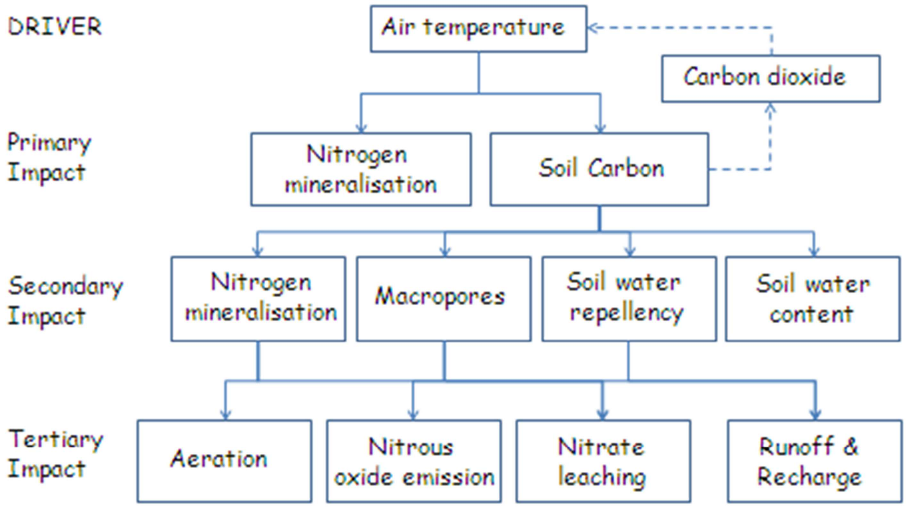

Figure 3: Direct and indirect impacts on the physical properties of soil from the driver of air temperature.

Soil types with a high carbon content are expected to have higher connected porosity on a macro scale than soil types with a low carbon content [8]. The connectedness of the macropores translates into greater diffusion of gases, which has potential to alter greenhouse gas emissions. Changes in macroporosity will have knock-on effects on soil aeration, nitrous oxide emission, nitrate leaching, plus runoff and recharge (Figure 3). For example, increased pore continuity has led to reduced levels of anaerobic activity and consequently lower nitrous oxide emissions in a pasture soil [9]. An increase in carbon content will generally improve water retention, except for soil types with a high clay content where the opposite effect can occur [10]. Changes in soil carbon content will also affect soil water content and water repellency. These, in turn, will affect rainfall runoff and groundwater recharge, Figure 3.

Clearly changes in amount and timing of rainfall will directly affect water content of soil (Figure 4). The changed pattern of soil water content will lead to altered patterns of drought and changed patterns in the ecosystem service of runoff and recharge. Drought will also contribute to greater water repellency of the soil further contributing to decreased soil moisture content.

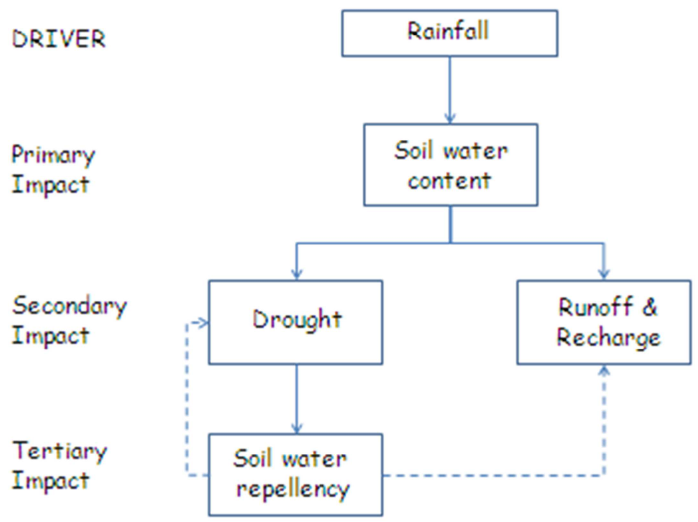

Figure 4: direct and indirect impacts on the physical properties of soil from the driver of rainfall.

Since soil carbon content has such important effects on the physical state of the soil it is arguably the most important manageable soil property. Maintaining soil carbon through land management will enable the delivery of appropriate ecosystem services in the face of changed air temperatures and rainfall patterns.

SOIL CHEMICAL STOCKS AND PROCESSES

Soil carbon stocks and cycling

Globally, soil represents a large and extremely important carbon reservoir (stock), larger than the atmospheric and vegetation carbon reservoirs combined. Carbon stocks present in New Zealand soil from the surface to a depth of 30 centimetres are estimated at 2890 billon of tonnes and are vulnerable to the changing climate. Carbon stocks are important for the long-term storage and cycling of organic matter and therefore productivity. Soil carbon is also a key component of soil physical natural capital.

Total carbon stocks

Limited information about New Zealand soil carbon exists, so predicting the magnitude of change on total carbon stocks by modelling of the effects of a changing climate on New Zealand’s total soil carbon have a low level of certainty. Although the soil carbon cycle has been well studied there is no clear understanding of the interactions between the factors controlling soil carbon stocks and climate change. Predictions made to dates indicate that:

- There will be little net change in soil carbon stocks [11] or possibly a reduction of 1.5% for production forests [12]. There are no modelled predictions for other sectors in New Zealand.
- Climate change will impact on soil carbon cycling processes which are strongly influenced by temperature and soil moisture.
- The net change in national soil carbon stocks, excluding erosion, is expected to be small, remain similar or decrease, over the coming centuries across sectors. Climatic extreme events will potentially have the greatest impact on soil carbon stocks under a changing climate, in particular through erosion.

Soil type effect

Soil type is an important consideration in determining climate change impacts on soil carbon stocks. New Zealand has a diverse range of soil types that are classified into 15 soil orders. These orders categorise soil types into groups of similar properties all of which influence soil carbon stocks. The highest levels of carbon stocks are found in Organic soil followed by Podzol soil and Allophanic soil and the lowest are found in weakly developed soil such as Recent soil and Raw soil. Under a changing climate, the susceptibility of the carbon stored in various soil types may be influenced differently as a result of how the soil carbon is protected or how easily the soil carbon is accessed for decomposition. For example soil types with low chemical activity (e.g. Recent soil and Raw soil) could potentially lose a higher percentage of soil carbon through accelerated decomposition under a changing climate than soil types where the majority of the soil carbon is well protected (e.g. Podzol soil and Allophanic soil). For soil types that have low soil carbon stocks, losing even a low percentage can negatively impact on the soil quality and the ability of the soil to function in providing ecosystem services. Conversely, for soil types that have a large soil carbon stock even a small percentage loss could result in a large amount of carbon released to the atmosphere resulting in a possible critically important feedback effect for future atmospheric carbon dioxide concentrations.

New Zealand's soil can contain protected soil carbon that has come from historical indigenous forest land cover. This soil carbon (old carbon) can be protected by the mineral soil for a considerable length of time, buffering any change (e.g. the spatial variability in historical soil carbon can be greater than the effects of current land-use changes [13]). The amount of historical protected carbon in different soil types is also varied and often uncertain, but, for some soil types the bulk of the soil carbon is from indigenous forest cover. Knowledge of how climate change affects impact on newly added soil carbon does exist but it is uncertain if historical protected soil carbon is less vulnerable to climate change due to a limited understanding of the mechanisms protecting historical soil carbon. Given that historical carbon can dominate the total stock in many New Zealand soil types, the effect of climate change on the historic carbon fraction should be of considerable interest. The potential for change in carbon stocks is large if the historic carbon fraction were liberated.

Soil carbon cycling

Soil carbon cycling processes are strongly influenced by temperature and soil moisture content, so will be affected by climate change. The initial source of carbon to the system is net primary production of plants. Additional processes then occur that deliver this plant carbon either on or below the soil surface (Figure 7).

Once it is part of the soil, carbon may undergo decomposition then be released as carbon dioxide to the atmosphere or may also be lost through dissolved organic carbon transport to ground water or through erosion. Alternatively, it may be stabilised in some way that prevents short- or long-term decomposition. The effects of climate change are expected to increase plant growth leading to greater carbon inputs through increased net primary production and also faster carbon decomposition rates. Impacts on soil carbon stabilisation and loss will vary. The effects of changes in these factors on various primary production sectors are summarised in Table 3.

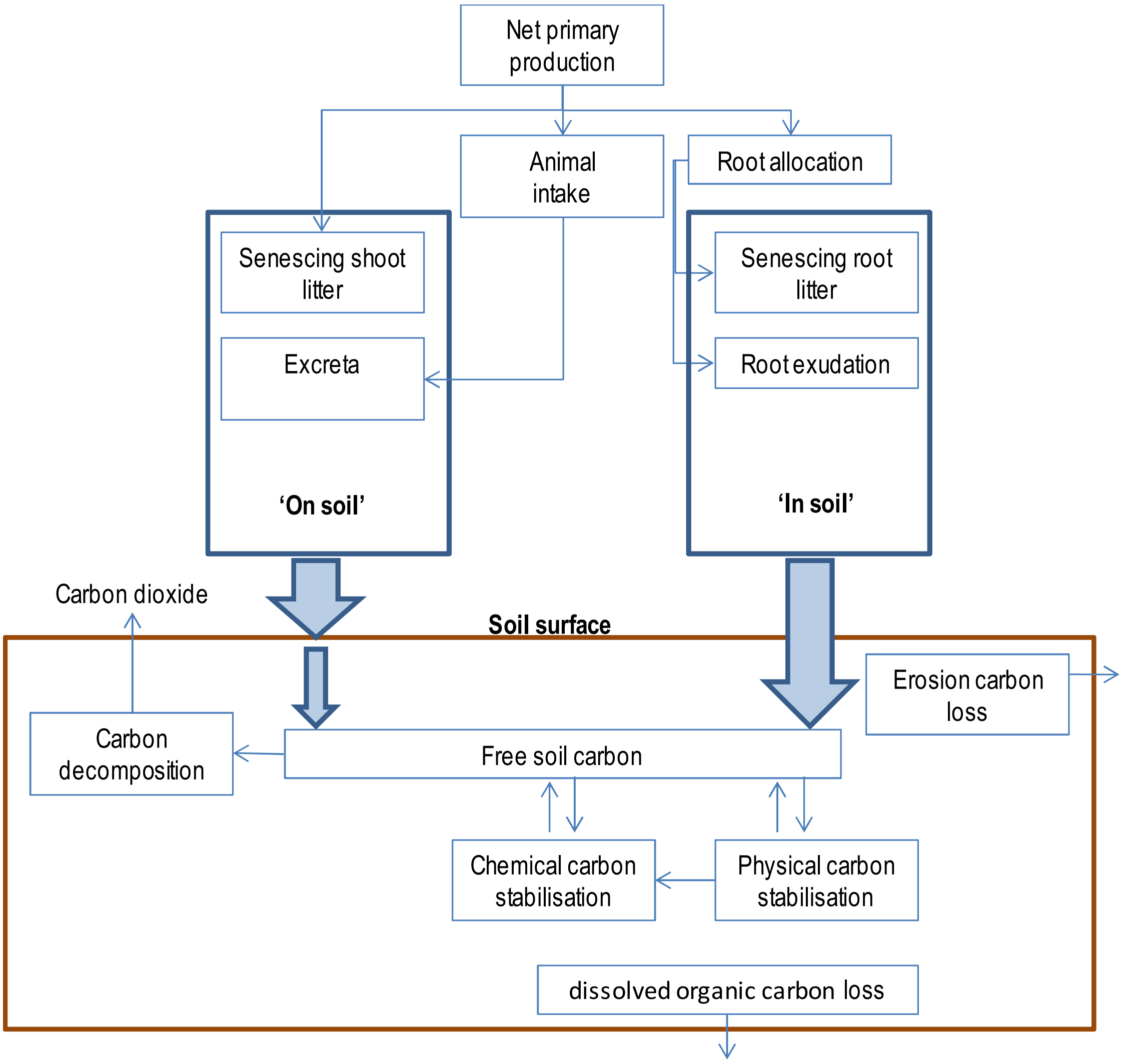

Figure 7: Key processes in the soil organic carbon (C) cycle in primary production systems.

Table 3: Summary of the impacts of climate change on carbon cycling and stocks for various primary production sectors.

Soil carbon factor	Production Sector			
	Cropping	Pasture intensive (e.g. dairy)	Pasture extensive (e.g. dry stock)	Forestry
Supply	↗	↗	↗	↗
Decomposition	↗	↗	↗	↗
Stabilisation	-	-	-	-
Loss from dissolved organic carbon	-	-	-	-
Loss from erosion	↗	→	↗	↗
Stock levels	→ ↘	→ ↘	→ ↘	→ ↘

Direction of change and certainty in science knowledge

- ↗ Overall, most likely to increase
- ↘ Overall, most likely to decrease
- → Overall, most likely to remain unchanged
- ↗ ↘ Could increase, remain unchanged or decrease
- \- Impacts are reasonably uncertain; therefore the direction of change cannot be predicted.

■ reasonably certain of effects

■ (grey) neither certain nor uncertain

Soil carbon supply

Plants can acclimatise to changes in temperature within a certain range, so in general, increased temperature will result in increased net primary production. Increases in temperature high enough to damage plants are not predicted for New Zealand. Temperatures low enough to limit plant growth should become less frequent. The effects of temperature on plant production are likely to be further modified over time as higher temperatures increase nutrient supply via greater mineralisation rates. This process may mitigate the expected effects of elevated carbon dioxide levels on nutrient limitation.

Water deficits will have detrimental effects on net primary production and biomass accumulation in all plant production systems. On the other hand, increased rainfall intensity can also reduce net primary production via excessive soil moisture levels and cause crop damage. Interactions between carbon dioxide levels, temperature and rainfall changes are readily observed and thus very important in determining actual future net primary production outcomes for any given location and species combination. For example, the effect of increased carbon dioxide levels on primary production is greater at higher temperatures. This positive effect will be enhanced under drier conditions if water-use efficiency increases. Little information is available on the effects of increased frequency of extreme weather events on net primary production, but it is reasonable to assume that more extreme conditions will reduce net primary production.

Changes in net primary production can be expected to translate directly into changes in overall carbon supply to the soil interface in terms of shoot litter, root inputs and animal excreta (in grazed pastures). However, the expected balance between these pathways may also change under climate change, with resultant impacts on the degree to which carbon is retained in soil. In particular:

- Root inputs are expected to increase compared to litter inputs under elevated carbon dioxide conditions. Soil carbon inputs from root turnover has implications for soil carbon stabilization if, as has been suggested, most soil carbon is derived from root inputs.
- Roots exude various compounds and these processes are expected to accelerate. Exudates contain easily decomposed carbon which may promote the decomposition of less decomposable carbon, reducing soil carbon stabilisation.
- The biochemical composition of the carbon supply to soil is likely to alter, with implications for the processes that decompose carbon in soil. Nitrogen-fixing plants (legumes) grow faster under elevated carbon dioxide conditions adding nitrogen to the soil. In the absence of legumes, the faster growth of plants under elevated carbon dioxide is expected to produce litter of a higher carbon to nitrogen ratio (i.e. less decomposable), reducing decomposition. However, this change is expected to have less impact on decomposition than the variation in litter availability with season.

Soil carbon decomposition

Soil microbes play an important role in carbon cycling by decomposing dead organic matter. A projected increase in temperature is expected to accelerate the decomposition of soil carbon but is dependent on the initial temperature. For example, the rate of decomposition increased more than six-fold at temperatures below 6 °C, but be less than four-fold above 10 °C [11]. Although the capacity of microbes to decompose organic carbon increases with increasing temperature, there may be less material available for decomposition at warmer times of the year.

Some forms of soil carbon are chemically inert and so are resistant to decomposition. Other forms may be physically contained within the matrix structure of soil so may also be less accessible to microbes. Understanding the effect of increasing temperature on the rate of decomposition of these "recalcitrant" forms of soil carbon is critical for understanding how soil ecosystems react to climate change. There is active debate over whether fractions with different recalcitrance have the same or different temperature dependencies. One possible theory is that the effect of increasing temperature on the rate of decomposition will increase with the recalcitrance of organic matter.

The rate of soil organic matter decomposition is linked to water availability, with decomposition processes inhibited in drier soil. This is an important interaction for two reasons. Firstly, climate change may cause changes in water availability through changed rainfall patterns. Secondly, increased temperatures due to climate change will lead to increased rates of water loss, and elevated carbon dioxide will lead to increased plant evapotranspiration. Consequently soil will be drier unless these changes are also accompanied by increased rainfall. The reduced levels of decomposition in drier soil should partly offset increased decomposition caused by higher temperatures, but this interaction has not yet been explored quantitatively.

Soil carbon stabilisation

Processes that stabilise carbon within soil do not lock it up indefinitely, just reduce the rate of carbon decomposition relative to unstabilised carbon. Such processes include physical containment of carbon within soil aggregates and chemical stabilisation by binding with clay minerals or metal oxides. Soil carbon stabilisation is indirectly influenced by climate change through impacts on the soil carbon supply and decomposition processes. Little is known about specific processes involved in soil carbon stabilisation and how these might respond to a changing climate. Both positive and negative responses are expected due to increasing temperature and changes in soil moisture.

Soil carbon loss

Carbon can be lost from soil through decomposition. Carbon can also be lost form the soil through the drainage of dissolved organic carbon and erosion. These processes will increase with climate change in areas with increased high rainfall events. Erosion negatively impacts on soil carbon through disturbance and removal from a site. More frequent extreme events will increase erosion [14] soil carbon losses, particularly in erosion-prone hill and steepland country. Soil carbon moved off site may become buried lower in the catchment or eventually in ocean sinks offsetting this loss.

Climate change will accelerate soil nutrient cycling

Soil nitrogen cycling

The effects of climate change on soil nitrogen cycling are partly dependent on soil organic matter content, carbon cycling and soil biota. Much of the nitrogen cycle is also influenced by soil floral/faunal communities. The ways in which nitrogen moves through the soil, plant and animals are complex and include many interactions and feedback loops (Figure 8). The nitrogen cycle is similar in pastoral, cropping and forestry ecosystems, but the relative size of different components will differ.

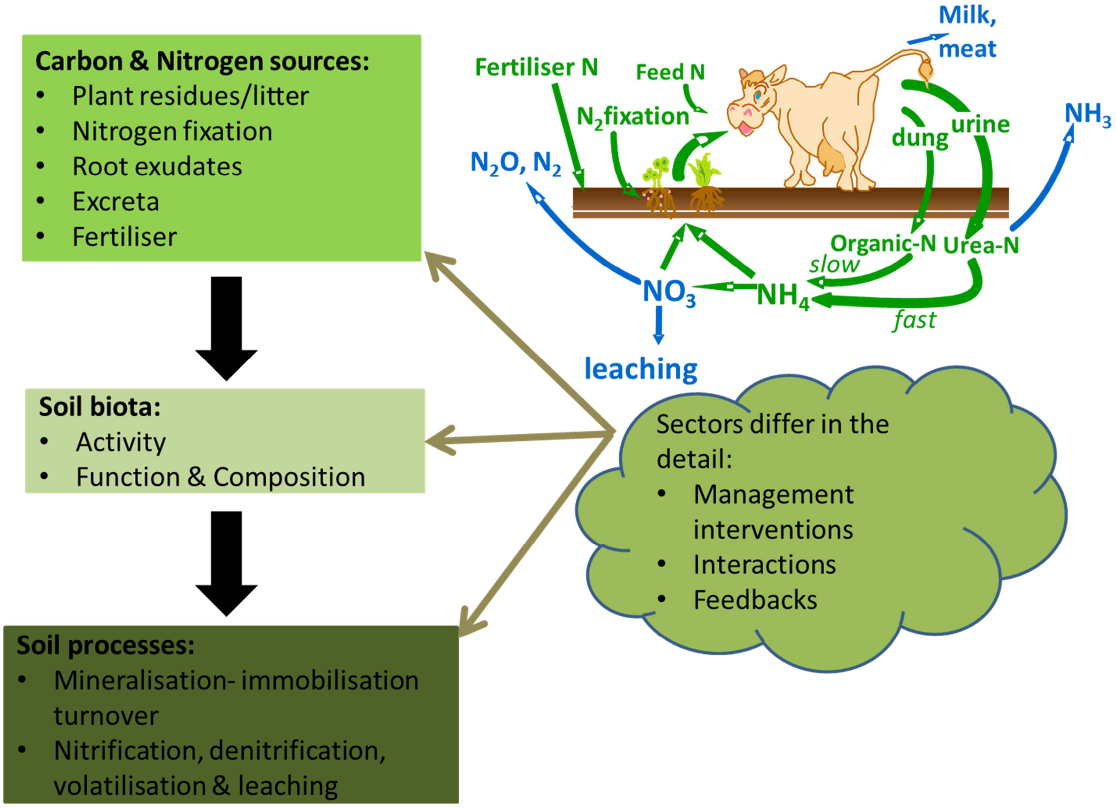

Figure 8: The nitrogen cycle, summarising the main sources and processes considered in this report.

The nitrogen cycle is made up of nitrogen inputs, processes and losses:

- *Inputs/transfer:* External (atmospheric inputs; nitrogen fixation; fertiliser), and recycled (crop residues; litter/root exudation; effluent ; excreta)
- *Processes:* Mineralisation immobilisation turnover (MIT); nitrification.
- *Losses/removal:* Gaseous ammonia; denitrification (of nitrogen and nitrous oxide); leaching of minerals containing nitrogen and dissolved organic nitrogen (DON).

Climate change impacts nitrogen cycling through elevated temperature, elevated carbon dioxide levels and changing rainfall distribution and amount. These impacts are further modified by an increase in extremes: more hot days, greater frequency of drought and more storm events. All these conditions will interact leading to a net overall effect on nitrogen transformations and processes. In considering the likely effects, it is important to factor in the difference between those responses generated in an experimental situation and the larger-scale response of the entire ecosystem (e.g. plant community structure). Experiments are useful for providing information about specific nitrogen processes but cannot really deal with interactions and complexity at the ecosystem level. Parsons et al. [15] provide a salutary warning:

> *"The complexity and time scales of response of this system defy understanding by observation and experiment alone, to the extent that attempts to manipulate the system without prior careful analysis of the potential outcomes, could prove at best ineffective, and at worst counter-productive."*

Bearing these limitations and associated uncertainties in mind, inputs of nitrogen are expected to increase with climate change, while the impacts of climate change on nitrogen processes, nitrogen losses and the availability of nitrogen for plant growth will be variable.

The impacts of climate change on soil nitrogen cycling inputs, processes and losses in various primary production sectors are summarised in Table 4.

Table 4: Summary of the impacts of climate change on nitrogen cycling.

Soil nitrogen factor		Production Sector			
		Cropping	Pasture intensive (e.g. dairy)	Pasture extensive (e.g. dry stock)	Forestry
Inputs/transfer	Atmospheric inputs	↗	↗	↗	↗
	Nitrogen fixation	↗	↗	↗	↗
	Fertiliser Nitrogen	↗	↗	→	↗
	Crop residues	↗	n/a	n/a	↗
	Litter/ root exudation	↗	↗	↗	↗
	Effluent Nitrogen	n/a	↗	n/a	n/a
	Excreta Nitrogen	n/a	↗	-	n/a
Processes	Net mineralisation	-	-	-	↗
	Nitrification	↗	↗	↗	-
Losses/removal	Product	↗	↗	↗	↗
	Ammonia (NH_3)	↗ (minor)	↗	↗	↗ (minor)
	Gaseous nitrogen (N_2) & nitrous oxide (N_2O)	↗	↗	↗	→
	Nitrate (NO_3^-)	↗ ↘	-	↘	↗ ↘
	Dissolved organic nitrogen (DON)		-	-	-

Direction of change and certainty in science knowledge

- ↗ Overall, most likely to increase
- ↘ Overall, most likely to decrease
- → Overall, most likely to remain unchanged
- ↗ ↘ Could increase, remain unchanged or decrease
- \- Impacts are reasonably uncertain; therefore the direction of change cannot be predicted.

- ■ reasonably certain of effects
- ■ neither certain nor uncertain

n/a Not applicable

Inputs

Inputs of nitrogen from the atmosphere are supplied to soil through rainfall so will increase if rainfall increases. Increases in ammonia volatilisation due to increasing temperatures may also lead to greater deposition of nitrogen. However it should be noted that, at a *system* level, there may be no net change due to volatilisation being replaced by deposition of nitrogen from an upwind source.

The amounts of plant residues and root exudates are likely to increase with increased biomass production under climate change. However, the effect of reduced quality of plant biomass due to a lower nitrogen content of residues (i.e. higher carbon to nitrogen ratio) is likely to be minor.

Nitrogen fixation will probably increase with climate change in areas with mixed grass/clover pastures or legume crops and also in forests with an understorey of leguminous (nitrogen-fixing) weeds. The number and mass of root nodules in various legumes (including white clover) will also increase leading to an increase in populations of associated rhizobia. Increased carbon dioxide levels led to an increase in the biomass of legumes in a free-air carbon dioxide enrichment (FACE) experiment conducted in New

Zealand [16] Nitrogen accumulation in grain-producing legumes in cropping systems also increased. Increased nitrogen fixation will result in an increase in nitrogen inputs into farm and forestry systems where legumes are present, as long as other nutrients (or water) are non-limiting. However, if more nitrogen is removed by harvesting grain than is fixed by the crop, then more soil and fertiliser nitrogen inputs may be required.

Increasing nitrogen inputs through the application of more fertiliser is an adaptive response to increased levels of carbon dioxide to ensure nitrogen availability does not limit crop yields. Furthermore, the increased production levels of pasture are likely to be fully utilised by increasing stocking rates and consequently additional amounts of excreta and effluent.

Processes

Climate change is expected to accelerate the turnover of nitrogen. For example, increases in temperature will increase nitrogen transformation rates unless limited by other key variables (e.g. moisture). Mineralisation-immobilisation turnover, nitrification, volatilisation and denitrification rates would all be expected to increase within the range of temperature increases predicted by various climate-change models. In contrast to temperature, elevated levels of carbon dioxide are unlikely to have any direct effects on process rates but there will be indirect effects on residue amount and quality that will affect carbon supply and biomass levels.

While the rate of mineralisation-immobilisation turnover is likely to increase, it is unclear whether climate change will result in net nitrogen immobilisation or net nitrogen mineralisation. Results of an analysis of various research studies indicate that elevated carbon dioxide levels are unlikely to increase microbial nitrogen immobilisation and have only a small effect on mineralisation. Nitrogen availability in low-nitrogen soil may increase as a consequence of these changes. Increased temperatures are likely to increase rates of nitrification rates. Elevated levels of carbon dioxide may have only small effects on nitrification. Overall, rates of nitrification will increase, although a decrease in net mineralisation will reduce the supply of ammonium ions available for nitrification, thereby limiting the net supply of nitrate.

The net effect of increasing temperatures and elevated carbon dioxide will be further modified by other environmental changes such as prolonged dry conditions in eastern regions and wetter conditions in western regions. Increases in the frequency of hot days and droughts are likely to reduce nitrogen transformations if water supply becomes limiting. Summer droughts will reduce growth and produce a flush of mineralisation on rewetting. This effect was observed in the NZFACE experiment [16]. No long-term effects of drought-induced dieback or fire in forests are expected as a result of climate change. However, open areas within forest will generally cause short-term increases in nitrogen mineralisation.

Nitrogen losses

The effect of climate change on nitrogen losses is reasonably simple to predict for purely temperature-driven processes. However, the net effect of processes also influenced by substrate supply and soil organisms is more difficult to predict. For example, an increase in nitrogen lost via ammonia volatilisation is predicted, due to increasing temperatures directly influencing this chemical process. However, there is less certainty about the effect of climate change on gaseous nitrogen losses via denitrification, as losses from this process will be influenced by the net supply of nitrate ions via nitrification. These may increase or decrease depending on whether net nitrogen immobilisation or net nitrogen mineralisation occurs. When considering the effect of temperature together with increased periods of rainfall and more water remaining in soil due to increased water-use efficiency by plants, it is likely that losses via denitrification will increase.

Changes in nitrogen leaching will be a balance between competing processes. Plants may reduce the amount of water uptake required for sustained growth due to increased water-use efficiency. Less water removal by plants will lead to increased soil water content, which may increase the risk of drainage and therefore leaching. However, an increase in plant production is likely to increase nitrogen uptake, thereby reducing the quantity of nitrogen available for leaching. Effects of increased rainfall will be greatest in regions where there is currently insufficient drainage to leach nitrogen below plant rooting depths. These same regions will also have increased risks of nitrogen leaching following intensive rainfall events. However, if climate change results in lower drainage, leaching will be reduced. There are large uncertainties associated with changes in nitrogen leaching because of the balance between competing processes (nitrification rates, nitrogen supply and uptake, rainfall and drainage). Also, it is highly probable that the effects will be site specific, depending on local rainfall patterns and rates of mineralisation immobilisation turnover and nitrification.

Whilst clearly the long-term average effects of changes in climate are important, it is important to consider the impacts of extreme effects such as increased frequency of storms and droughts. Uncertainty around the timing and amount of rainfall and the likelihood of extreme (hot) temperatures will limit agricultural and forestry productivity, overriding any consideration of the effects on nitrogen-cycling processes in extreme seasons.

Progressive nitrogen limitation (including nutrient limitations)

Progressive nitrogen limitation (PNL) is a soil-nitrogen limitation process that occurs in low-nitrogen soil. As the name suggests, nitrogen becomes limited over time as a result of increased nitrogen uptake due to enhanced plant growth. While increased carbon dioxide levels stimulate plant productivity in the short term, productivity may be limited over longer periods by an insufficient supply of nitrogen. This effect will occur because more soil nitrogen will become sequestered into plant tissue and immobilised by soil organic carbon, resulting in a negative feedback loop to plant growth. Immobilisation by soil organic matter is partly dependent on soil carbon stocks increasing with time. However, it is unclear whether soil carbon stocks will increase, remain constant, or decline over time. Recent modelling of a forestry system suggests that soil carbon stocks are more likely to remain constant or decline [12]. In such situations, progressive nitrogen limitation will be more variable and may only occur if the amount of nitrogen is sequestered into plant biomass in sufficient quantities.

The nature and magnitude of external nitrogen inputs and the initial nitrogen status of the ecosystem will critically determine if and when progressive nitrogen limitation occurs. This process is unlikely to occur in ecosystems that receive substantial external inputs (such as fertiliser nitrogen in cropping and intensive pastoral systems). There is less information available on the likelihood of a nitrogen limitation occurring on managed pastures receiving fertiliser nitrogen inputs of around 200 kg of nitrogen per hectare each year. The productivity of nitrogen-fixing legumes and other nitrogen fixation processes may increase with elevated levels of carbon dioxide, which may offset some progressive nitrogen limitation. Progressive nitrogen limitation is also probably less likely to occur in ecosystems where soil carbon stocks are declining. Interestingly, signs of progressive nitrogen limitation were observed by decreasing pasture yields during the first four years of the NZFACE experiment on a low nitrogen input pastoral system [16]. Drought-breaking rainfall 'reset' the system in year 4 causing a flush of mineralisation. However, signs of progressive nitrogen limitation were again observed in subsequent years.

Progressive nitrogen limitation has the potential to have a major effect on the accuracy of predictions about the impact of climate change on soil nitrogen cycling. In turn, this will affect predictions about the relative effects of climate change on net primary production, i.e. will increased levels of carbon dioxide have a sustained fertiliser effect? However, progressive nitrogen limitation is unlikely to occur if nitrogen supply is already limited to the extent that plants do not respond positively to increased levels of carbon dioxide.

This potential impact is not restricted to nitrogen, but is also applicable to other potentially limiting nutrients, particularly phosphorus. A compilation of different studies suggested that only when there were increases in net primary production (often indirectly through nitrogen addition) does climate change have an effect on decreasing phosphorus availability [17]. However, given the generally low plant available phosphorus levels in New Zealand soils, and evidence from the NZFACE site that phosphorus may be limiting [18], further confirmation of the role of phosphorus in progressive nutrient limitation is warranted.

Soil chemistry

The rate of soil chemical reactions will increase as soil temperature increases. The chemical reactions that occur rapidly on an annual basis are leaching of nutrients, change of pH, loss of silicates, reduction/oxidation (redox) reactions, changes to mineral surfaces, and changes to soil organic matter.

Elevated carbon dioxide levels can cause acidification (lower pH) of soil indirectly through increased root and microbial respiration [19]. This increase in acidity then leads to increased weathering and leaching of nutrients deeper into the soil. It is important to note that pH is externally controlled by application of lime in some production lands so changes in this soil property may be insignificant.

A major uncertainty in how climate change affects global carbon cycling is the combined effect of organic activity, temperature, and atmospheric carbon dioxide on silicate weathering. Experimental studies of how fast some minerals dissolve have indicated that dissolution of silicates in organic-rich solutions (a measure of silicate weathering) is not directly affected by soil carbon dioxide but is very sensitive to temperature. Increasing levels of carbon dioxide may accelerate silicate weathering indirectly by the increased production of organic acids. Also, weathering of silicate minerals may consume carbonic acid and thereby remove atmospheric carbon dioxide more rapidly with increasing temperature [20].

Accelerated leaching of silicates from volcanic-ash soil types or South Island montane soil types may lead to increased production of aluminium silicate clays and aluminium-humus complexes. These processes may possibly lead to increased phosphorus retention but the timeframe for these changes is uncertain. Leaching of cations may also increase. Calcium bicarbonate is a dominant salt in pasture soil. Bicarbonate ions are produced by respiration from carbon decomposition and loss of bicarbonate will also result in loss of calcium. Sodium and chloride ions often dominate in forest soil as sea salt is wind-blown inland. Losses of other cations in forest soil will depend on the soil parent minerals and their mineralogy. Changes in soil carbon have a large impact on cation-exchange capacity [21] (the ability of the soil to hold on to positively charged compounds such as calcium and magnesium), so any reduction in soil carbon will reduce the capacity of soil to retain nutrients.

Soil nutrient cycling

More rapid nutrient cycling and possible decreases in soil pH are likely to occur under climate change making ecosystems more susceptible to loss of some nutrients. Increased net primary production as a result of increased levels of carbon dioxide may reduce nutrient losses through increased plant uptake. There is also likely to be increased nutrient inputs from recycled plant residues and root deposition. In grazed pasture, additional nutrients will be available as a result of increased levels of excreta. Changes in the composition and amount of soil organic matter will have a large impact on nutrient retention.

The complex interactions between plants, microbes and soil make it difficult to predict the effects of climate change on nutrient cycling with any certainty. For example, different plant species will vary in their physiological responses to climate change and this variability will affect not only below-ground processes but also the composition and stocks of soil organisms. The way in which particular plant species respond to climate change will also affect the quality of resulting plant residues. However, changes in the quality of plant residues are likely to be less important than changes in residue quantity. It must be remembered that the quantity of plant residues has also been shown to affect microbial community composition. The balance of nutrients in the soil itself can affect microbial functioning. For example, lack of sufficient nutrients (primarily nitrogen or phosphorus) can limit rate of microbial processing.

Overall, climate change will result in a many competing effects that will have a direct bearing on nutrient supply and retention. There is also considerable debate as to whether or not the diversity of soil organisms is likely to influence ecosystem processes so the consequences for ecosystem services remain unclear. Uncertainty also exists about how changes in organism diversity will affect soil but there is more clarity about how climate change will affect the composition of soil biotic communities and nutrient dynamics. Mycorrhizal fungi vary in the extent to which they enhance nutrient availability, as well as the quality and quantity of carbon they produce. Changes in the composition of mycorrhizal communities are therefore likely to alter the amount of carbon stored in ecosystems. Irrespective of specific results, a number of studies have indicated that changes in the composition and activity of soil organisms in response to climate change are likely to have a significant effect on nutrient supply.

SOIL BIOLOGICAL STOCKS AND PROCESSES

The organisms (biota) that inhabit soil are diverse, numerous and interact in complex food webs (Figure 5) that strongly influence soil processes. Any changes to soil that disrupt the biodiversity and/or functioning of soil organisms will have profound influences on the flow of ecosystem services from soil natural capital. Changes in temperature and moisture will directly and indirectly affect soil organisms. Indirect effects to soil biota include changes to soil chemistry and structure, and plant community composition that in turn, affect the biota. These changes could potentially be greater than direct effects. The direction and magnitude of indirect effects are very difficult to quantify because food webs are extremely complex and certain effects will be species specific. Lack of reliable information in this area is one of the major knowledge gaps on how climate change will affects soil natural capital and soil processes.

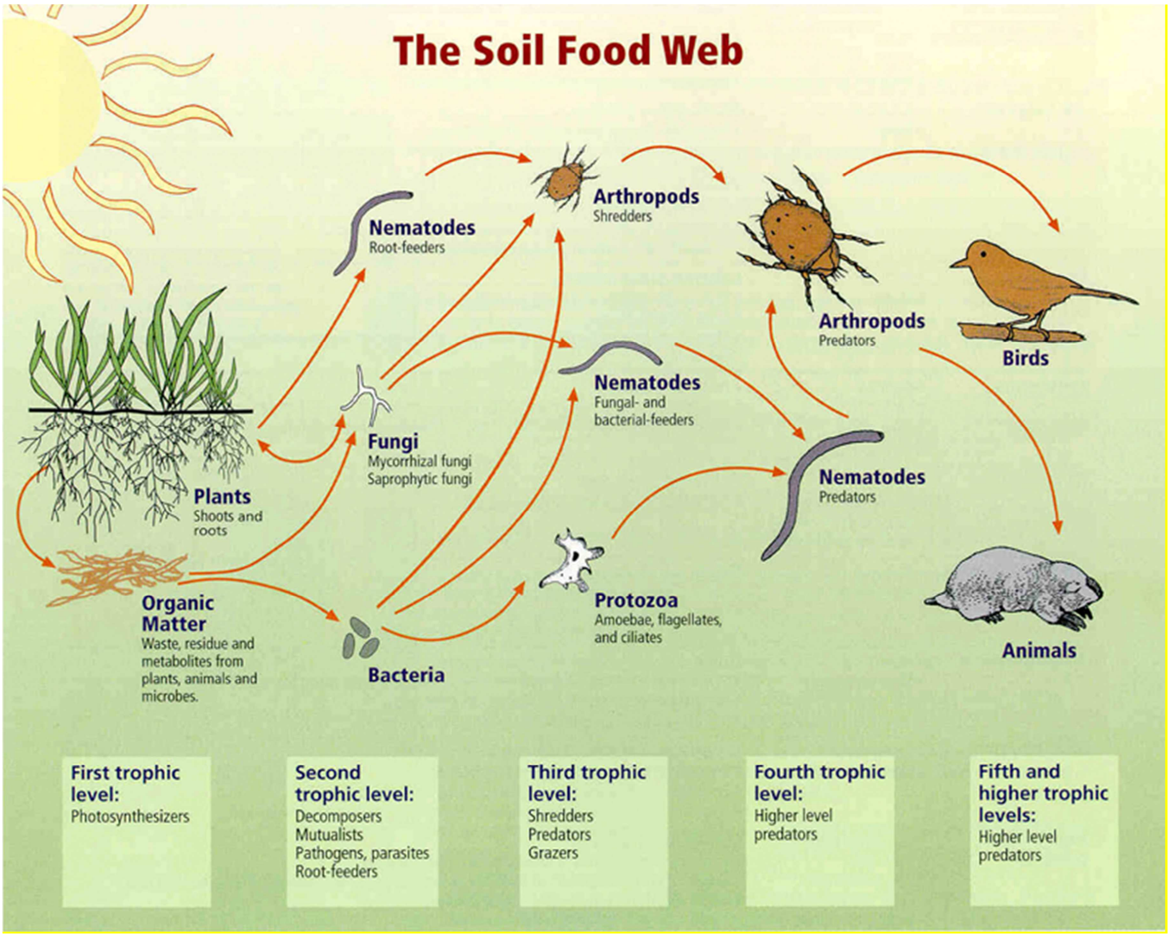

Figure 5: An example of a soil food web. Image courtesy of the United States Department of Agriculture Natural Resources Conservation Service.

Elevated atmospheric carbon dioxide levels are unlikely to have a direct effect on soil organisms given the much greater levels and fluctuations that exist in soil pores and pore water. Indirect effects of elevated carbon dioxide on soil organisms are likely to be mediated via changes in plant community composition, production and subsequent litter quality and quantity. This section summarises the effects of climate change on three important groups of organisms: soil invertebrates (arthropods, nematodes and earthworms), bacteria and fungi.

An estimation of sector relevance is provided in Table 5 as a summary of the impacts of climate change on soil processes, taking into consideration the interaction of carbon and nutrient cycling. All primary production sectors will be affected by climate change. However, the impacts of climate change on cropping and intensive pastoral sectors are expected be lower than those for the extensive pastoral and forestry sectors. In particular, both the composition and biomass of soil organisms and plant behaviour will change across all sectors.

Table 5: The impacts of climate change on soil processes considering the interactions between plants and soil organisms. The colours of the boxes represent which sectors are most likely to be impacted. ***There is a reasonable certainty of a change occurring in some sectors but there is high uncertainty in both the direction and magnitude of any changes.***

Factors potentially affected by climate change	Processes influenced by factors	Probability (by sector) that change to a factor will sufficiently affect a process to a relevant degree				Justification
		Cropping	Dairy	Extensive grazing	Forestry	
Species diversity or richness						
Plant	Organic matter decomposition					Greater potential for change in species diversity and less nutrient management in extensive grazing and forestry
	Nutrient cycling					
	Carbon dioxide and methane flux					
Soil biota	Organic matter decomposition					Species richness can influence decomposition rates in extensive grazing and forestry systems
	Nutrient cycling					Some nutrient pathways are narrow and there is potential for species diversity to significantly influence availability
	Carbon dioxide and methane flux					No change likely due to probable functional redundancy - except for importance of methanotrophic bacteria in forestry systems
Species Biomass						
Plant	Organic matter decomposition					Changes to biomass likely in all systems. Negative changes in the cropping and dairy sectors will be minimised by management practices
	Nutrient cycling					Any effect in the cropping and dairy sectors is likely to be overwhelmed by nutrient-management practices
	Carbon dioxide and methane flux					Likely changes across all sectors
Soil biota	Organic matter decomposition					Significant responses likely in all cases due to change in rates of activity with altered abundances
	Nutrient cycling					
	Carbon dioxide and methane flux					
Species Composition						

Plant	Organic matter decomposition					Greater potential for species composition change in forestry than cropping and dairy sectors and even more so in extensive grazing
	Nutrient cycling					Greater potential for species composition change in extensive grazing and forestry due to less nutrient management in these sectors
	Carbon dioxide and methane flux					Greater potential for species composition change in forestry than cropping and dairy sectors and even more so in extensive grazing
Soil biota	Organic matter decomposition					Important across all sectors due to influence on many soil functions
	Nutrient cycling					Some nutrient pathways are highly influenced by species composition, importance moderated by fertiliser use
	Carbon dioxide and methane flux					Important across all sectors due to regulation
Plant Behaviour (changes in productivity, carbon inputs, and litter quality)						
	Organic matter decomposition					Important across all sectors due to influence on many soil functions
	Nutrient cycling					Less nutrient management in extensive grazing and forestry
	Carbon dioxide and methane flux					Important across all sectors due to regulation

Direction of change and the probability that change to a factor will sufficiently affect a process to a relevant degree

Relatively high probability of change

Moderate probability of change

Low probability of change

Little is known about how climate change will affect the soil biota that control carbon and nitrogen cycling processes

Soil Invertebrates

Soil invertebrates include arthropods, nematodes and earthworms. Some climate change impacts on soil invertebrates in general are included, but this section focuses largely on nematodes and earthworms. Nematodes are a family of small worms that collectively are the most abundant animals on Earth. Soil invertebrates can either feed on organic matter and bacteria (decomposers) or live plant material (grazers). Some groups of Nematodes in particular are considered pests as they feed on plant parts (primarily roots) and can decrease plant yield. Earthworms feed on dead organic material and are important for a healthy soil as they mix organic matter and nutrients in the soil as they burrow.

The largest effects on soil invertebrates from elevated carbon dioxide levels will be the indirect effects from changes in plant production and litter quality. In general, an increase in the abundance of both decomposer and plant feeding soil invertebrates has been linked to an increase in plant growth from elevated carbon dioxide. An increased abundance of plant-feeding soil invertebrates, however, could lead to increased consumption of plants. This effect may limit any gains in plant yield from elevated carbon dioxide levels. Increases in invertebrate abundance may be lower or non-existent in nutrient-limited systems. In one study of increased carbon dioxide levels, earthworm casts contained lower concentration of nitrogen, indicating a reduced ability to utilise lower quality substrate for food although population levels were not directly affected [22].

Increases in temperature with future climate change are likely to have a range of effects on soil invertebrates, depending on the optimal temperature of individual species. Some species may reproduce more frequently resulting in increases in population size. The geographic distribution of species will also be affected. Changes in geographic range of some species will have little impact on productive sectors, but for others (e.g. pest species) the consequences may be negative. For instance, the distribution of the clover-root knot nematode is predicted to increase under certain climate change scenarios (Figure 6). This species is a pest because it feeds on a clover causing large reductions in yield of this important pasture component.

Direct effects of changes in soil moisture on invertebrates include changes in activity (movement, reproduction) and indirect effects are those on plant productivity and quality. Earthworms require a moist, well-aerated soil and irrigation of dry land increases their abundance. Climate change leading to increased rainfall is likely to have the same effect to some extent. Conversely, for those areas where rainfall is reduced, earthworm abundance and activity are likely to decline. Extreme events such as drought will exacerbate such impacts.

Any reduction in decomposition by soil fauna as a result of climate change will impact not only nutrient cycling but possibly also the health of grazing livestock (due to increased incidence of facial eczema – a condition caused by microbes that proliferate on plant litter).

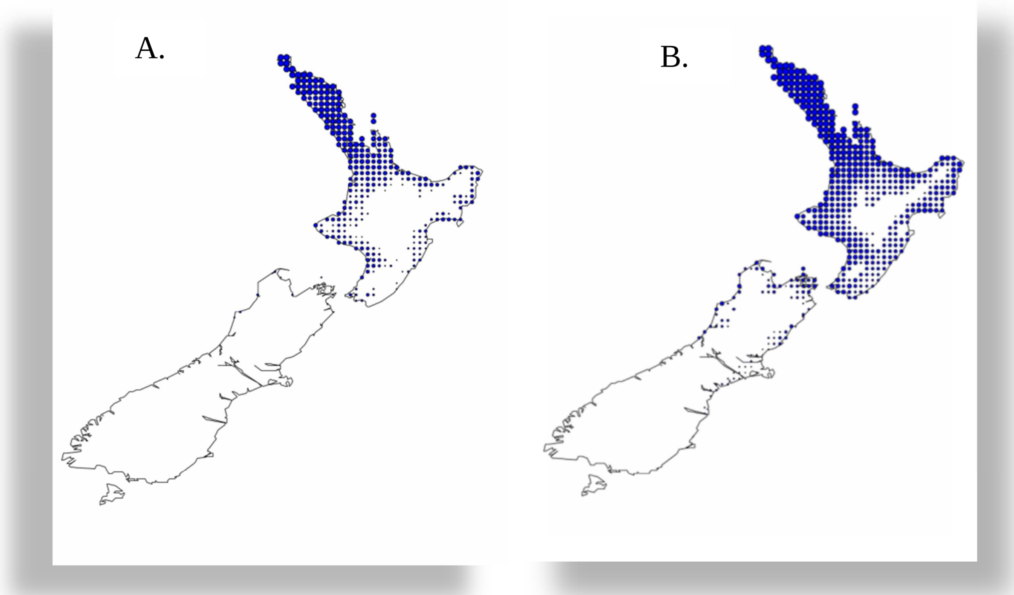

Figure 6: Predicted distribution of clover root knot nematode from a simulation model. A: using 1961-1990 temperature and moisture levels; B: using 2070 levels predicted using a moderate climate change scenario. ***Notice that under climate change the range of the pest is much greater in the North Island and extends to portions of the South Island.***

Bacteria and fungi

The diversity of microbial communities in soil is the highest of any ecosystem. Microbial communities play key roles in various critical ecosystem processes, such as trace gas formation, carbon cycling and sequestration, decomposition, soil nitrogen cycling, and disease suppression. Climatic factors such as temperature and soil moisture are important controls affecting microbial life in soil. Unfortunately, there is no straightforward answer to the question of how these processes will be affected by climate change.

The microbial composition of low-nutrient systems often changed very little in laboratory experiments that varied carbon dioxide and temperature levels. Systems with high-levels of nutrients (by applying fertiliser) may to be more sensitive to change. Results from field experiments that varied more than one climate factor at a time indicate that elevated levels of carbon dioxide have more effect on microbial communities when combined with changes in temperature and moisture than alone.

Results from field experiments have varied but bacterial abundance may increase with increased temperature in the presence of elevated carbon dioxide. Consequently, a climate-change scenario with increased temperatures, carbon dioxide and rainfall may cause a shift in the overall microbial community towards a bacterially dominated system. However, other studies considering a single factor (such elevated carbon dioxide levels) have suggested an increase in fungi. The results are likely to be dependent upon the specific land use (and possibly nutrient availability within that land use) of the community under study.

Soil type also affects the structure, diversity and range of most soil microbial communities, largely because of differences in soil acidity. However, adjustment of soil acidity is already common practice in many agricultural sectors so little effect is expected as a result of climate change.

Here we focus on how climate change will affect two bacterial communities of major importance to primary sector productivity. Rhizobia are important for nitrogen fixation in ryegrass/clover pasture systems. Ammonia-oxidising bacteria convert ammonium (NH_4^+) ions into nitrate (NO_3^-) ions that are a key source of nitrogen nutrition. The importance of different groups of fungi on soil ecosystem processes is also examined.

Rhizobia
White clover takes nitrogen from the air and fixes it in the soil through a symbiotic relationship with *Rhizobium* species of bacteria. New Zealand's pastoral agriculture sector is highly dependent on this process. There is strong evidence that increases in atmospheric carbon dioxide will lead to increases in biological nitrogen fixation under non-limiting soil nutrient conditions. Results from one study showed that *Rhizobium* species exhibited increased nitrogen fixation under elevated carbon dioxide conditions, but only when phosphorus was added to the system. In contrast, a reduced proportion of atmospheric nitrogen was fixed under elevated carbon dioxide conditions in the NZFACE experiment [16]. The reasons for these different results are not known but there is evidence that suggests that phosphorus may be as limiting to plant production as nitrogen at the NZFACE site [18]. Effects are likely to depend on the specific species of bacteria involved as some species are more efficient at fixing nitrogen than others.

Ammonia-oxidising bacteria
Ammonia-oxidising bacteria convert ammonium ions into nitrate ions. This process is the rate limiting step of nitrification so Ammonia-oxidising bacteria have a central role in global nitrogen cycling.

In a field study monitoring high levels of carbon dioxide (emitted from vents), a change in the composition of the ammonia-oxidising bacteria community resulted in a decrease in soil-nitrification potential [23]. However, it was suggested that this effect was due to indirect changes in the input of soil carbon from plants. This again illustrates the large impact indirect effects can have on the biotic community and soil processes

One study found that plant species composition had a larger effect on ammonia-oxidising bacteria richness than soil warming, but a clear relationship between ammonia-oxidising bacteria richness and potential nitrification could not be found [24]. Another study manipulated multiple climate-change factors. The abundance of ammonia-oxidising bacteria decreased with elevated carbon dioxide levels, but the decrease was most pronounced when rainfall was increased. Increases in nitrification were associated with shifts in the composition of the ammonia-oxidising bacteria community but not changes in abundance [25].

Fungal communities
Soil fungal communities can be divided into three major functional groups based on their source of carbon: mycorrhizal fungi, saprotrophic fungi, and pathogenic fungi. It is important to note that productive forests in New Zealand have a relatively low fungal diversity compared to forests overseas. This low diversity is due to the non-native origin of the most widely gown forest species radiata pine and Douglas-fir and their limited capability to utilise native fungi. This could potentially make the New Zealand forestry sector more vulnerable to changes in fungal communities as a result of climate change than might be inferred from studies of these trees in their native Northern Hemisphere ranges.

Mycorrhizal fungi
Mycorrhizal fungi are a symbiotic relationship between plants and fungi. Fungi acquire carbon from the plant while the plant acquires nutrients from the fungi. Most plant species used in agricultural and horticultural applications rely on mycorrhizal fungi. Mycorrhizal fungi can represent 5 – 50% of soil microbial biomass associated with some crops. Up to

100% of a plant's phosphorus uptake may be obtained through mycorrhizal hyphae. Mycorrhizal fungi are also very important in the forestry sector with radiata pine and Douglas-fir both highly dependent on specific ectomycorrhiza for successful establishment after planting.

Under elevated carbon dioxide, increased mycorrhizal biomass has been a common but not universal finding. Increased mycorrhizal biomass can enhance the ability of the plants to obtain nutrients which may be an advantage if nutrient limitation occurs.

Increased temperature can increase mycorrhizal fungal abundance and root infection, but response to temperature is species specific. Similarly their ability to acclimate to higher temperatures also differs. Mycorrhizal fungi tend to make plants more resistant to drought (though the mechanism for this is not known), but again this varies by species.

Changes in mycorrhizal abundance may also affect soil carbon levels. In the short term, an increased biomass may result in net soil carbon loss [26]. However, models suggest that longer-term accumulation of recalcitrant compounds derived from mycorrhizal fungi may result in net carbon gain [27].

Saprotrophic fungi

Saprotrophic fungi are important because they decompose complex sources of carbon and can have very high species diversity. Soil with a high level of fungal biomass generally leaches less nitrogen and emits less nitrous oxide than poorer soil. In addition to recycling of soil nutrients, saprotrophic fungi may play a role in suppression of pathogenic fungi.

Saprotrophic fungi typically occur in microhabitats with extremely high levels of carbon dioxide so they are unlikely to be directly affected by elevated carbon dioxide levels. There are few studies of fungal responses to soil moisture, thought at least one study found that soil fungi are more responsive to increased soil moisture than soil bacteria, resulting in increased biomass and greatly increased relative dominance of fungi with increased soil moisture [28]. The response to increased temperatures (as well as interactions between carbon dioxide, temperature and rainfall) is also unknown as there is little evidence to suggest how changing climate conditions in New Zealand will affect these fungi.

Pathogenic fungi

Fungi and fungi-like organisms (e.g., *Phytophthora* species) are very common causes of plant disease, resulting in a significant cost to the primary productive sector in New Zealand. There are predictions that global climate change will contribute not just to the spread and effects of existing disease, but also to the rate of emergence of new diseases. The recent example of a fungal disease (Psa) in kiwi fruit highlights the vulnerability of some sectors of New Zealand's agricultural economy. Some data indicate that elevated carbon dioxide levels and increased temperatures can positively enhance plant resistance to fungal infection, but there are few data available on individual pathogenic species and no proposed mechanism for how this occurs.

Impact on land management

How will land management be impacted by climate change?

The primary focus of this report is to present climate change impacts on soil processes, natural capital and regulating services. However, it is appropriate to provide a comment on potential changes to land management practices to ensure water or nutrients do not become limiting, and pests or diseases do not increase. Land management and land use will change according to the risks and opportunities presented to land owners and stakeholders. This adaptation is likely to have a greater impact on soil natural capital than any climate change impacts.

Brinkman, and Sombroek [29] state that “in most cases, changes in soil by direct human action, on-site or off-site (whether intentional or unintended), are far greater than the direct climate-induced effects”. Therefore, management measures designed to optimise the sustained productive capacity of soil would be generally adequate to counteract any degradation of agricultural land by climate change. Soil in undeveloped areas or other land with a low intensity of management is less readily protected against the effects of climate change. However, such soil is threatened less by climate change than by human actions, such as excessive nutrient extraction under very low-input agriculture.

The main effect of climate change on agricultural and forestry systems is an increase in net primary production of plants. The most likely and important limitations to increased net primary production are:

- Progressive nitrogen limitation, where nitrogen from legumes cannot meet nitrogen shortfalls.
- Increased risk of storm events, droughts, and forest fires, pests and diseases.
- Increased temperatures affecting animals in grazed systems.

Adaptation options for New Zealand’s land based sectors have been described by Clark et al. [7]. Land owners will adapt to these limitations through changes to land management and land use. Such changes may include, but are not restricted to:

- Greater nitrogen fertiliser use and/or increased legume use, where progressive nitrogen limitation affects pasture, crop and forestry production.
- Increased irrigation for crop and pasture production in the dry eastern regions of New Zealand and possibly northern regions.

There will also be sector-specific land management adaptations:

- *Pastoral* may include the development of feed strategies to meet shortfalls due to increased frequency of summer drought, increased stocking rates to utilise extra pasture production and increased steps to minimise adverse effects of hot days on animal performance.
- *Forestry* afforestation may increase in erosion-prone steep hill country. Increased use of herbicides to control nitrogen-fixing shrub-weeds, such as gorse and broom.
- *Cropping* Land management and land-use changes may include reduced tillage to conserve soil moisture, modifying crop species or genotype selection, crop rotation in response to the changing climate, and development of new overseas markets.

Possible changes to policy or regulation, such as restrictions on use of nitrogen fertiliser or water, have not been factored into any of these management responses.

New technologies to maintain and enhance productivity could improve soil natural capital. For example, exploring future targets for efficient use of nutrients will become an important consideration for New Zealand's land based sectors, as more nitrogen will be needed to capture potential benefits from increased levels of carbon dioxide. On the other hand, there may be trade-offs with future adaptations resulting in reduced natural capital. An example of this is the potential for expansion of irrigation onto soil that is susceptible to sediment loss, erosion and compaction. This could be triggered if irrigation enables sloping paddocks to be more intensively grazed.

"Changes in land management are likely to have a greater impact on soil natural capital than changes in climate"

Recommendations for future research

What are the recommendations for future research to ensure the prosperity of soil services in New Zealand's primary land based productive sectors under a changing climate?

Based on this review and the identification of knowledge gaps, future research in the following areas is recommended:

Soil natural capital and processes

1. Improve the understanding of soil biota and how they respond to climate variables in order to obtain improved projections on carbon and nitrogen cycling processes.
2. Develop more reliable national models to project changes in soil natural capital spatially across New Zealand, including soil carbon stocks by soil type.
3. Improve the understanding of soil carbon stocks and turnover rates of active (labile) carbon and protected carbon and how interactions of nutrients (nitrogen and phosphorus) and plant/microbial communities affect these pools.
4. Improve the understanding of interactions between increased carbon dioxide, increased temperature and changes in rainfall on soil processes at the farm system scale.
5. Improve the understanding of how spatial variability at a local scale (e.g. paddock urine patch dynamics on pasture; distribution of nitrogen in soil) influences nitrogen supply and losses under a changing climate.
6. Improve prediction of droughts and drought-breaking rain and their impacts on nitrogen cycling under different land-use sectors across a range of regions.
7. Improve and understand the impact of climate change on nitrogen-fixing plants and their ability to increase soil nitrogen for plant growth, focusing on species (e.g. mixed sward pastures, legumes) that New Zealand's economy is highly reliant on.
8. Improve the understanding of climate change effects on soil biota and inclusion of biotic controls of carbon and nutrient cycling in models.
9. Incorporate relationships between nutrients (e.g. a stoichiometric approach that quantifies limits of multiple nutrients (carbon, nitrogen, phosphorus and calcium) on soil biota and functioning) into climate change models. Limitation of more than one resource is a key factor limiting adaption to land use and climate change.

Soil ecosystem services

10. Continue to develop soil indicators that can be used to measure ecosystem services to improve the projection of climate change impacts on soil services.

Land management

11. Establish base-line levels of soil natural capital to allow for an assessment of land management responses to climate change.

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Appendices

Appendix 1. Technical report.

Appendix 2. List of the workshop participants.

Appendix 3. List of acronyms and abbreviations.