Technical Report
Project NT011

NATIONAL INSTITUTE FOR
FOREST PRODUCTS INNOVATION

Natural Capital Risk Assessment – Australian Forestry

2021

Launceston Centre
Funded by the Australian Government, Tasmanian Government & Industry Partners.
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Natural Capital Risk Assessment – Australian Forestry

Prepared for

National Institute for Forest Products Innovation

Launceston

by

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Publication: Natural Capital Risk Assessment – Australian Forestry

Project No: NIF076-1819 [NT011]

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ISBN: 978-0-9586704-3-2

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Final report received by NIFPI in March 2021

This work is supported by funding provided to Forest and Wood Products Australia (FWPA) to administer the **National Institute for Forest Products Innovation** program by the Australian Government Department of Agriculture, Water and Environment and the Tasmanian Government.

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Department of Agriculture, Water and the Environment

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Executive summary

Natural capital *is the stock of renewable and non-renewable natural resources such as soil, water and biodiversity that yield flows of environmental goods and services which directly and indirectly underpin the global economy and human wellbeing (Natural Capital Coalition 2016)*

This report develops and applies a standardised framework for natural capital risk assessment in forestry, in order to produce the **first systematic, evidence-based assessment of natural capital risks for the Australian forestry sector**. It focusses on primary production and therefore excludes any additional natural capital risks associated with transport, downstream processing, use or disposal of timber products. Although the report focusses on forests managed primarily for wood production, the approach and assessment results can also be applied to forests that are managed primarily for conservation, restoration or other purposes.

A healthy forest depends on a variety of ecosystem services provided by natural capital, such as productive soil, adequate supplies of water and a suitable climate. Changes in the availability of these natural capital **dependencies** can threaten the productivity of forests, and thus the financial viability of forestry companies. At the same time, while sustainably managed forestry has the potential to maintain or increase natural capital, less well managed forestry has the potential to have substantial **impacts** on natural capital. This can also affect the financial position of a forestry company if an activity negatively affects natural capital that the business itself depends on (such as degrading soil quality on their own land), or when society responds to natural capital impacts through regulation (such as fines) or changes in consumer acceptance (such as restricted access to certain markets in the absence of sustainability certification).

Risk *is the "uncertain consequences, particularly possible exposure to unfavourable consequences" (Hardaker et al. 2015)*

Dependencies and impacts on natural capital can therefore create a variety of **direct risks** for forestry companies, which translate into **indirect risks** for private or public sector investors in those companies. Businesses and investors are increasingly expected, by regulators, standard-setters and society in general, to take natural capital into account in their decision-making (Smith et al. 2020). Improved management of natural capital can also create **opportunities** for forestry companies and investors, for example in activities which have lower risk exposure, or in new markets resulting from society's transition to better management of natural capital. The focus of this report is on risk, but similar principles can be used to guide assessment of opportunities.

This report sets out a framework for natural capital risk assessment in the forestry sector, building on existing approaches, based on mapping the forestry sector's dependencies and impacts on natural capital, and assessing the **materiality** of risks associated with these, for a given geographical area (Australia). By providing both a forestry-specific approach and an initial materiality assessment of the Australian forestry sector's natural capital risks, this report aims to simplify, streamline and standardise the process of natural capital risk assessment for individual forest estates within Australia. The information produced by standardised natural capital risk assessments could be used in a variety of ways, by stakeholders including forestry operators, investors and lenders, and regulators (covering both governments and non-governmental bodies such as sustainability standard-setters), as follows:

Materiality is interpreted broadly as "anything that has reasonable potential to significantly alter the decisions being taken" (Ascui and Cojoianu 2019b)

Forestry operators	**Forestry investors and lenders**	**Forestry regulators**
• Improve risk management and thus resilience to natural capital related shocks • Access natural capital finance opportunities (Smith et al. 2020) • Standardise natural capital related reporting to investors, regulators and other stakeholders	• Identify and evaluate the most material natural capital risks associated with forestry investments • Allocate capital more efficiently and thus increase portfolio returns • Standardise natural capital related reporting to financial regulators and other stakeholders	• Assess the resilience of their forestry industries in a standardised way • Streamline information requirements across multiple reporting standards • Standardise natural capital related reporting

Using expert knowledge and a review of academic and industry literature, we identified 20 key natural capital risk areas for forestry, associated with ten impact and ten dependency pathways. We assessed the evidence for materiality of risks associated with each pathway separately for the softwood plantation, hardwood plantation and native forest sub-sectors (Table 1-1).

Overall, the assessment found that the materiality of risks associated with natural capital dependencies (natural capital that forestry businesses depend on) were generally moderate to high. By contrast, the materiality of risks associated with impacts (natural capital that forestry businesses impact on) were mostly low to moderate, with softwood and hardwood plantations having similar profiles, slightly different to the profile for native forests.

The most material risks for Australian forestry were associated with water availability, temperature, bushfire, storms and floods, soil quality and pests and diseases (for all sub-sectors), and biodiversity (for native forests). All of these highly material risks arise from natural capital dependencies, apart from biodiversity which was an impact risk for native forests only, and bushfire and soil quality which were both a highly material dependency risk and impact risk. In the past, most environmental management attention within primary industries such as forestry has focussed on impacts. Our analysis suggests that greater awareness of the importance of dependencies will be important to achieving more comprehensive risk management in future.

Climate change is an underlying driver of environmental change affecting all of the most highly material dependencies, whilst also potentially exacerbating biodiversity and pests and diseases impacts. Changes in rainfall regimes, temperature regimes and associated changes in fire regimes and the distribution of pests and diseases pose a combination of direct and indirect risks for the industry. The Australian Prudential Regulation Authority (APRA) has already identified climate change as a material issue for the financial sector in Australia, largely reflecting its indirect exposure to climate risks affecting other sectors of the economy (APRA 2019). This report expands on this and identifies the set of natural capital impact and dependency risks that are potentially material for the Australian forest industry and its stakeholders, including the financial sector, governments and regulators.

Our materiality assessment shows that although the potential scope of natural capital dependencies and impacts for an industry such as forestry is vast, it can be simplified, in this case to just twenty key risk areas of relevance to Australian forestry, of which only seven have been assessed as highly material for each industry sub-sector. This means that forestry companies, investors and other stakeholders can focus available resources on more cost-effective assessment and management of a small set of highly material risks, which can be gradually expanded over time. Further research should target priority risks where a lack of evidence, or uncertainty in the available evidence, leads to a higher materiality assessment than might otherwise be the case, in order to be conservative.

Finally, it should be noted that the conclusions of this materiality assessment are generic and only applicable at sector level, in Australia, and at the current point in time. Materiality assessments at individual company or estate level, and/or sector level in other geographies, may differ. However, a materiality assessment at sector level provides a simplified starting point and guide to undertaking more detailed risk assessment at individual estate level.

A subsequent report will explore potential indicators and sources of data for assessing, monitoring and reporting natural capital impact and dependency risks. Such indicators should adequately represent each risk and data should be cost-effectively practicable to obtain. Ideally, indicators and data sources should be harmonised across the industry and meet the needs of all relevant stakeholders, in order to reduce transaction costs and promote trust in the reliability, consistency and comparability of reported information.

Table 1-1 Summary of materiality assessment of Australian forestry natural capital impact and dependency risks, by sub-sector

Thematic area	Risk area	Definition	Materiality		
			Softwood plantations	Hardwood plantations	Native forests
Water	Water availability (dependency)	The risk that rainfall, or groundwater resources, will be insufficient to produce the target volume and quality of harvestable biomass.	**High**	**High**	**High**
	Water use (impact)	The risk that water extracted beyond its renewal rate, or diverted away from other ecosystem uses.	**Moderate**	**Moderate**	**Low**
	Water quality (impact)	The risk that forestry activities negatively affect the quality of surface or sub-surface water.	**Low**	**Low**	**Low**
Weather and climate	Temperature (dependency)	The risk of lower productivity and/or increased costs due to exposure to changes in average temperatures, or temperature extremes.	**High**	**High**	**High**
	Bushfires (dependency)	The risk of lower productivity and/or increased costs due to exposure to bushfires.	**High**	**High**	**High**
	Bushfires (impact)	The risk that forest activities, such as prescribed burning, may increase the incidence of fire in the surrounding areas.	**Moderate**	**Moderate**	**High**
	Storms and floods (dependency)	The risk of lower productivity and/or increased costs due to exposure to storm events, for example floods, storms, hail, snow, cyclones.	**High**	**High**	**High**
Land and soil	Soil quality (dependency)	The risk of lower productivity and/or increased costs due to poor soil quality.	**High**	**High**	**High**
	Soil quality (impact)	The risk that forestry activities negatively affect soil quality.	**High**	**High**	**High**
	Fertiliser use (dependency)	The risk that non-renewable inputs to fertiliser may be priced at higher levels in future.	**low**	**Moderate**	**N/A**

Thematic area	Risk area	Definition	Materiality		
			Softwood plantations	Hardwood plantations	Native forests
	Contamination and waste (impact)	The risk that land is contaminated with various forms of waste.	**Low**	**Low**	**Low**
Biodiversity and ecosystems	Biodiversity (dependency)	The risk of lower productivity and/or increased costs due to loss of ecosystem services provided by biodiversity.	**Moderate**	**Moderate**	**Moderate**
	Biodiversity (impact)	The risk that forestry activities may negatively affect biodiversity or habitats.	**Moderate**	**Moderate**	**High**
	Weeds (dependency)	The risk of lower productivity and/or increased costs due to weeds.	**Moderate**	**Moderate**	**Moderate**
	Weeds (impact)	The risk that forestry activities increase the incidence or impact of weeds.	**Moderate**	**Moderate**	**Low**
	Pests and diseases (dependency)	The risk of lower productivity and/or increased costs due to pests and diseases.	**High**	**High**	**High**
	Pests and diseases (impact)	The risk that forestry activities increase the incidence or impact of pests and diseases.	**Low**	**Low**	**Low**
Energy	Energy (dependency)	The risk of lower productivity and/or increased costs due to inefficient use of energy and/or higher prices of energy inputs.	**Low**	**Low**	**Low**
Air emissions	Greenhouse gas emissions (impact)	The risk that emissions of greenhouse gases may be priced at higher levels in future, reflecting true costs of climate change, or that regulations will limit future GHG emissions.	**Low**	**Moderate**	**Moderate**
	Other air emissions (impact)	The risk that other air emissions (such as particulates and volatile organic compounds) may be priced at higher levels in future, or regulations will limit future emissions.	**Low**	**Low**	**Moderate**

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1. Introduction

1.1 Natural capital impacts, dependencies and risks

Primary industries such as forestry can have significant **dependencies** and **impacts** on natural capital – the stock of renewable and non-renewable natural resources and ecosystems (such as soil, water and biodiversity) that yield flows of environmental goods and services which directly and indirectly underpin the global economy and human wellbeing (Ascui and Cojoianu 2019b).

At a business level, financial, operational, reputational, regulatory or societal risks can arise as a result of business dependencies and/or impacts on natural capital. These **direct risks** for businesses translate into **indirect risks** for private or public investors in those businesses.

Improved management of natural capital can also create **opportunities** for forestry companies and investors, for example in activities which have lower risk exposure, or in new markets resulting from society's transition to better management of natural capital. The focus of this report is on risk, but similar principles can be used to guide assessment of opportunities.

Dependencies: A dependency is a "business reliance on or use of natural capital" (Natural Capital Coalition 2016 pp.16-17). For example, forestry companies depend on adequate rainfall and soil suitable for growing crops or trees. Dependencies on natural capital are not commonly explicitly recognised by businesses. Risks can arise for the business when important dependencies are threatened by environmental or social changes, such as climate change resulting in different rainfall patterns, or changes in agricultural practices altering the availability of land for new plantations. Managing such changes can result in increased costs, such as increasing fertiliser application to improve soil nutrition. In extreme cases, lack of availability of a critical dependency can make a business unviable.

Impacts: An impact is a "negative or positive effect of business activity on natural capital" (Natural Capital Coalition 2016 pp.16-17). For example, forestry activities such as harvesting can impact soil and water quality. Risks can arise for the business if an activity negatively affects natural capital that the business itself depends on (such as degrading soil quality on their own land), or when society responds to environmental impacts through regulation or changes in consumer acceptance. For example, negative impacts on natural capital could result in regulatory penalties or a company losing a sustainability certification, thus restricting its access to certain markets.

1.2 Natural capital risk assessment

Businesses and investors are increasingly expected, by regulators, standard-setters and society in general, to take natural capital into account in their decision-making (Natural Capital Declaration 2012, Natural Capital Coalition 2016, Smith et al. 2020). Two critical inputs to many business decision-making settings are an understanding of the **value** of different options, and an understanding of the **risks** associated with those options. Value and risk are interconnected, as the level of risk adjusts the value of any asset and determines the required rate of return on investments. **Natural capital accounting** is the process of measuring and valuing natural capital and ecosystem services so that this information can be included in decision-making. **Natural capital risk assessment**, on the other hand, is the process of measuring and assessing the level of risk associated with an entity's impacts and/or dependencies on natural capital. The conventionally measured financial value of the business can be used as the base to which any natural capital risk adjustment applies; or the underlying value of the business can also be adjusted using natural capital accounting (RSPB 2017, Forestry Commission 2018, Forico and IDEEA Group 2018).

Natural capital risk assessment is a relatively new concept, and consistent approaches have only recently begun to emerge. The Natural Capital Protocol (Natural Capital Coalition 2016) provides a generic approach to undertaking any type of natural capital assessment, including risk assessment, although it does not provide specific guidance on how to do this. A supplement to the Protocol, tailored to the forest products sector, is also available (Natural Capital Coalition 2018). More specific guidance, based on the Natural Capital Protocol, has been developed by the Natural Capital Finance Alliance (NCFA) for portfolio risk assessment (NCFA and PwC 2018, NCFA and UN Environment World Conservation Monitoring Centre 2018) and individual asset-level risk assessment in agriculture (Ascui and Cojoianu 2019b).

This report builds on all of these, in particular the NCFA guide to natural capital risk assessment in agriculture, to provide a framework for natural capital risk assessment in the forestry sector, based on mapping the forestry sector's dependencies and impacts on natural capital, and assessing the materiality of risks associated with these, for a given geographical area (Australia). An impact, dependency, or risk arising from either of these is **material** to a business (or an investor in that business) if it can substantively influence business (or investor) decisions.

1.3 Purpose and structure of this report

This report aims to provide a **systematic, evidence-based assessment of natural capital risks for the Australian forestry sector**. It focusses on primary production and therefore excludes any additional natural capital risks associated with downstream processing, transport, use or disposal of timber products. Although the report focusses on forests managed primarily for wood production, the approach and assessment results can also be applied to forests that are managed primarily for conservation, restoration or other purposes.

Using a combination of literature review and expert assessment, the report systematically identifies and describes risks arising from forestry's dependencies and impacts on natural capital and assesses the materiality of these risks for each of the three main types of forestry in Australia: native forests, hardwood plantations and softwood plantations.

By providing both a worked example of a forestry-specific approach and an initial materiality assessment of the Australian forestry sector's natural capital risks, this report aims to simplify, streamline and standardise the process of natural capital risk assessment for individual forest estates within Australia. A simplified and streamlined approach makes individual assessments more feasible and cost-effective, while standardisation increases the comparability and credibility of assessments, thus increasing stakeholder confidence in the results.

The information produced by standardised natural capital risk assessments could be used in a variety of ways, by stakeholders including forestry operators, investors and lenders, and regulators (covering both governments and non-governmental bodies such as sustainability standard-setters), as follows:

Forestry operators	Forestry investors and lenders	Forestry regulators
• Improve risk management and thus resilience to natural capital related shocks • Access natural capital finance opportunities (Smith et al. 2020) • Standardise natural capital related reporting to investors, regulators and other stakeholders	• Identify and evaluate the most material natural capital risks associated with forestry investments • Allocate capital more efficiently and thus increase portfolio returns • Standardise natural capital related reporting to financial regulators and other stakeholders	• Assess the resilience of their forestry industries in a standardised way • Streamline information requirements across multiple reporting standards • Standardise natural capital related reporting

The report is structured as follows. Section 2 sets out our methodology. Section 3 provides, for each major risk category, a definition of the risk, an explanation of its principal causal pathway(s), a review of the evidence, links to other risks, our materiality assessment, and a summary of risk mitigation options. Section 4 concludes with our overall findings and recommendations.

2. Methodology

This report applies the methodology for a sector/region-level natural capital risk assessment as set out in the Natural Capital Finance Alliance (NCFA) guide for agriculture (Ascui and Cojoianu 2019b), which in turn is based on the generic assessment methodology of the Natural Capital Protocol (Natural Capital Coalition 2016) (Figure 2-1 below).

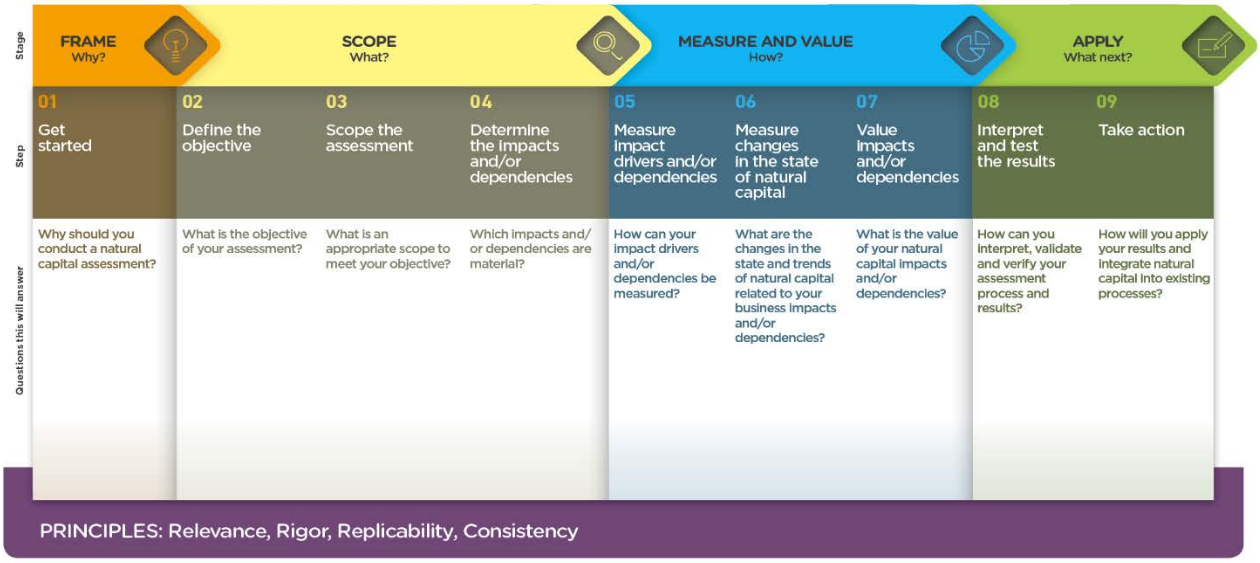

Figure 2-1 Four Stages of the Natural Capital Protocol.

Source: (Natural Capital Coalition 2016).

The first ‘frame’ stage of the Protocol calls for clarification of the reasons for conducting a natural capital assessment. Our primary reason for conducting this forest natural capital risk assessment is **to identify the materiality of natural capital dependencies and impacts, and their associated risks, for Australian forestry operations.**

We define risk as;

“*uncertain consequences, particularly possible exposure to unfavourable consequences*” (Hardaker et al. 2015).

This definition acknowledges that risk may involve both negative and positive outcomes, although in practice, risk assessment typically focusses on understanding the likelihood of significant negative outcomes.

The NCFA defines materiality as:

“Materiality is interpreted broadly as anything that has reasonable potential to significantly alter the decisions being taken” (Ascui and Cojoianu 2019b).

The main output of stage 2 of the Protocol is a **materiality assessment**, defined as “the process that involves identifying what is (or is potentially) material in relation to the natural capital assessment’s objective and application” (Natural Capital Coalition 2016, p. 43). Given that our objective is to understand natural capital risk at an industry/region-level (Australian forestry), materiality assessment in this context involves assessment of the risks associated with forest natural capital dependencies and impacts. In a different context with different objectives, it might (for example) involve identifying the largest or most valuable pools of natural capital affected by the business.

Materiality assessment is applicable at two stages in the Protocol: first in scoping which potential impacts and/or dependencies to include in an assessment, then again as part of the evaluation of an assessment (stage 3). Our research into forest natural capital risks has likewise been iterative and open to either including new impacts or dependencies or rejecting initial assumptions, as further evidence was gathered. Similarly, any user of the risk assessment framework developed in this report should undertake their own materiality assessment and tailor the identified material risks to their own operations.

The Protocol provides a generic methodology for undertaking a materiality assessment (Natural Capital Coalition 2016), comprising the following steps:

1. List potential natural capital impacts and/or dependencies;
2. Identify materiality criteria;
3. Gather relevant information; and
4. Complete the materiality assessment.

Step 1 invokes the concepts of impact and dependency pathways. The concept of impact pathways is well developed (PwC 2015, Natural Capital Coalition 2016): it involves identifying impact drivers (which may be inputs to or outputs from business activities, e.g. air emissions)[1], the environmental outcomes or changes in natural capital that result from the impact driver (e.g. an increase in levels of a pollutant), and the resulting societal impacts (e.g. health problems). The concept of dependency pathways is somewhat less well developed, but we can likewise identify pathways that lead from various drivers of environmental or social change (e.g. a build-up in chemicals which are harmful to pollinating insects) to changes in natural capital (e.g. fewer pollinating insects), which in turn affects the availability of ecosystem services (e.g. pollination) on which a business depends (see Figure 2-2 below). We take a broad view of ecosystem services including provisioning (e.g. production of timber), regulating (e.g. water regulation), cultural (e.g. recreation) and supporting (e.g. soil formation) services (Millennium Ecosystem Assessment 2005). In some cases, the relevant 'service' might be the *absence* of conditions that would otherwise be unfavourable. Likewise, some ecosystem services may have negative effects on a business (such as pests and diseases) and can therefore be considered 'ecosystem dis-services'. These are also important to consider from a risk perspective.

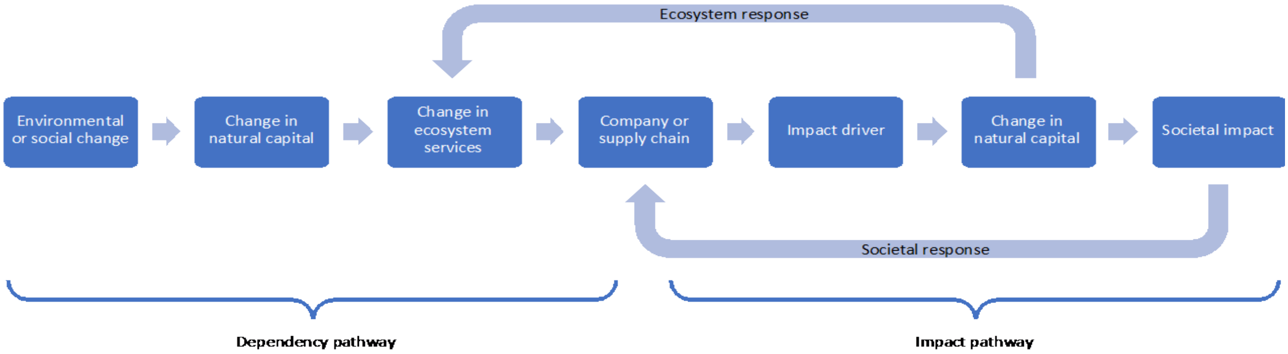

Figure 2-2 Dependency and impact pathways.
Source: (Ascui and Cojoianu 2020).

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[1] The Natural Capital Protocol defines impact drivers as "a measurable quantity of a natural resource that is used as an input to production… or a measurable non-product output of business activity (Natural Capital Coalition, 2016, p. 44). We believe this definition is too narrow on the output side, as it seems evident that certain products (e.g. pesticides) can have an impact on natural capital in and of themselves, and not only through their non-product outputs.

It is important to note that the word ‘impact’ can be used in different ways: the specific sense of an impact on natural capital as opposed to a dependency on natural capital; and the more generic sense of a harmful effect on something (e.g. a change in availability of an ecosystem service can be said to have an impact (positive or negative) on the business that depends on it). As the specific sense is widely used in natural capital assessments, to avoid confusion, we use the term ‘effect’ where possible to denote the general sense.

It is also important to note that although impacts on natural capital are sometimes generally described as ‘outputs’, and dependencies as ‘inputs’, these terms only apply at a systemic level when considering the relationship between ‘business’ and ‘natural capital’, and not at the individual level of inputs or outputs to production processes. Both inputs and outputs to production processes may cause impacts on natural capital, and likewise both inputs and outputs may depend on natural capital – for example, as the source of inputs of natural resources, or in terms of environmental assimilation of certain levels of waste outputs.

The Natural Capital Protocol Forest Products Sector Guide (Natural Capital Coalition 2018) provides the following examples of potentially material natural capital impact drivers and dependencies, which we used as a starting point. We supplemented this with a review of the dependencies identified as material for Australian forestry in the online natural capital dependency risk assessment tool, ENCORE.[2]

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[2] https://encore.naturalcapital.finance/ (accessed 5 March 2020).

Table 2-1 Examples of potentially material impact drivers.

Source: (Natural Capital Coalition 2018, p. 40)

Business input or output	**Impact driver category**	**Examples of specific, measurable impact drivers**
Inputs	Water use	Volume of groundwater consumed, volume of surface water consumed
	Terrestrial ecosystem use	Area of agriculture by type, area of forest plantation by type, area of open cast mine by type, etc.
	Freshwater ecosystem use	Area of wetland, ponds, lakes, streams, rivers or peatland necessary to provide ecosystem services such as water purification etc.
	Marine ecosystem use	Area of aquaculture by type, area of seabed mining by type, etc.
	Other resource use	Volume of mineral extracted, volume of wild-caught fish by species, number of wild-caught mammals by species, etc
Outputs	GHG emissions	Mass of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), sulphur hexafluoride SF4), hydroflurocarbons (HFCs) and perfluorocarbons (PFCs), etc.
	Non-GHG air pollutants	Mass of fine particulate matter (PM2.6) and coarse particulate matter (PM10), volatile organic compounds (VOCs), mono-nitrogen oxides (NO and NO2 commonly referred to as NOx), sulphur dioxide (SO2), carbon monoxide (CO), etc.
	Water pollutants	Mass discharged to receiving water body of nutrients (e.g. nitrates and phosphates) or other substances (e.g. heavy metals and chemicals)
	Soil pollutants	Mass of waste matter discharged and retained in soil over a given period
	Solid waste	Mass of waste by classification (e.g. non-hazardous, hazardous, and radioactive), by specific material constituent (e.g. lead, plastic) or by disposal method (e.g. landfill, incineration, recycling, specialist processing).
	Disturbances	Decibels and duration of noise, lumens and duration of light, etc, at site of impact

Table 2-2 Examples of potential dependencies.

Source: (Natural Capital Coalition 2018, p. 41)

Business inputs	Dependency category	Specific dependencies
Consumptive	Energy	Solar, wind, hydro, geothermal, biofuel, fossil fuel
	Water	Fresh water (ground, surface, rain) or sea water
	Nutrition	Human or animal food
	Materials	Wood fibre, genetic resources, metals, minerals, plant and animal materials
Non-consumptive	Regulation of physical environment	Flood attenuation, water quality regulation
	Regulation of biological environment	Crop pest control, pollination
	Regulation of waste and emissions	Waste assimilation, noise and dust regulation
	Experience	Nature-based recreation, tourism
	Knowledge	Information from nature (e.g. for biomimicry)
	Well-being and spiritual/ethical values	Employee satisfaction and stress release, sacred sites and indigenous traditions that support company staff or operations

Due to practical limitations to the scope of this report, we focussed on forestry's **direct** dependencies and impacts, while recognising that there is also potential for **indirect** dependencies or impacts that could be mediated via other businesses or production processes that interact with forestry throughout the supply chain.[3]

For each potentially material direct impact driver and ecosystem service (as initially identified or subsequently suggested from review of other sources), we mapped out the rest of the impact or dependency pathway. A literature review was then used to provide an evidence-based assessment of the materiality of the identified dependencies and impacts. Literature reviewed included academic papers (searched via Web of Science and Google Scholar) and forest industry publications, searched via Google.

We assessed the materiality associated with each pathway separately for softwood plantations, hardwood plantations and native forests. To provide clarity, whenever we refer to a softwood or hardwood plantations, we are specifically referring to the plantation area (i.e. the spatial extent of the plantation trees) rather than a whole forestry company. This is important to note because it is common in Australia for forestry companies to own and manage mixed estates of both plantation and native

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[3] An example of an indirect interaction could be a forestry company's dependency on a supplier of spare parts for harvesting equipment – we have not considered the supplier's impacts or dependencies on natural capital.

forest. For such companies which own mixed estates, they may need to consider the evidence and materiality scores for their plantation separately to their native forest.

A natural capital impact or dependency is defined as material in the Protocol if "consideration of its value, as part of the set of information used for decision making, has the potential to alter that decision" (Natural Capital Coalition 2016, p. 43). Any assessment of materiality is therefore to some degree subjective and context-dependent. We considered a number of different approaches to provide more consistency in our impact/dependency materiality assessment. For example, (NCFA and UN Environment World Conservation Monitoring Centre 2018) consider materiality of a dependency to be a combination of the significance of the loss of functionality in the production process if an ecosystem service is disrupted, and the significance of the financial loss due to the loss of functionality in the production process.

However, assessing the materiality of a potential *risk* is different to assessing the materiality of a dependency (as per (NCFA and UN Environment World Conservation Monitoring Centre 2018)) or an impact (as per (PwC 2015), because it requires not only an assessment of causal pathways, but the likelihood of adverse outcomes. For example, availability of oxygen would have to be considered a highly material dependency for human beings, but it would not normally be considered a material risk in the course of everyday activities where the availability of oxygen is unlikely to be limited.

Essentially, a risk materiality assessment requires a preliminary or high-level risk assessment, the purpose of which is to delineate the scope of risks that should be assessed in more detail in a specific risk assessment, for example, for a given forestry company, or a given forest estate.

The level of a risk is typically considered to be a function of its **likelihood** and the **magnitude or severity of consequences (including social misperceptions of this)**. However, in the case of a risk materiality assessment, it is not necessary to evaluate in detail the likelihood of a risk occurring. In order to delineate the scope of risks that should be assessed in further detail, it is sufficient to consider whether the occurrence of a risk is plausible, over a relevant time-scale, which in the case of forestry we have taken to be 10-30 years. A risk is considered to be plausible if it has occurred in the past or in similar situations elsewhere, or if it is projected to occur in future. If the likely future occurrence of a risk is scientifically highly uncertain, we have erred on the side of caution and considered it plausible.

We therefore focused on the magnitude or severity of consequences, which we defined primarily as **adverse financial impacts on a typical forestry company resulting from a change to an ecosystem service on which the forestry company depends, or a change to an impact driver**. Financial loss is the primary means of transmission of natural capital risk to investors and lenders. For example, a risk that could destroy a significant proportion of a forest estate would be considered to have high potential severity, whereas a risk that could only increase costs slightly would be considered to have low potential severity. However, in some cases (mainly to do with natural capital impacts), investors or lenders could be affected more indirectly (e.g. through reputational damage)—where relevant this should be taken into account.

A major challenge facing any evidence-based natural capital risk materiality assessment is the general paucity of evidence that explicitly links dependency or impact pathways to the probability of financial loss for affected companies. However, there are three main ways in which the overall financial position of a forestry company could be negatively affected: through decreased yield or productivity, higher costs, or lower prices for products (Ascui and Cojoianu 2019a). Each of these could occur in different ways: for example, a company could experience lower prices for its products due to a reduction in quality, increased competition, or through being excluded from markets. In our review of evidence, we therefore widened the criterion of financial loss to include adverse deviations in yield, prices or costs, for which more evidence is available.

Our assessment of the potential magnitude or severity of business consequences is a subjective judgement based on the totality of the evidence reviewed. However, in order to make this judgement more rigorous and consistent, we have taken a systematic approach, summarised in Table 2-3 below. For impact pathways, we have separately assessed the **degree of impact** of forestry operations on the relevant stock of natural capital or flow of ecosystem services and the **severity of consequences** of such impacts (for the financial viability of the forestry company). For dependency pathways, we have assessed the **degree of dependence** of a typical forestry company on the relevant stock of natural capital or flow of ecosystem services and the **severity of threats** to the same. In both cases, it is the combination of degree of impact/dependence and severity of consequences/threats that indicates the level of risk materiality for the forestry company directly, and thus for an investor indirectly.

Table 2-3. Assessment approach for determining materiality: high level categorisation

Impact risk	Degree of impact	Severity of consequences	Overall risk materiality assessment
Dependency risk	Degree of dependence	Severity of threats	

The degree of impact was assessed by considering to what extent the relevant stock of natural capital or flow of ecosystem services could continue to function after a plausible impact. A high degree of impact would indicate the natural capital or ecosystem service is likely to be significantly damaged and unable to repair itself without costly intervention. The severity of consequence was assessed based on how significantly the company could be affected by any societal or ecosystem response to the impact (see Figure 2-2 above). It is worth noting that consequences occurring through the 'ecosystem response' pathway, for example, where impacts degrade natural capital that the company itself depends on are also considered in the degree of dependency (below). We take this conservative approach to ensure all risks are considered when determining the materiality of each topic.

The degree of dependence was assessed by considering to what extent the company could continue to function without the relevant natural capital or ecosystem services. A high degree of dependence would indicate the company's function would be significantly impaired, and substitutes either do not exist or are only available at significantly higher prices. The severity of threat was assessed by considering the significance of plausible changes for the future availability of the relevant natural capital or ecosystem services. Factors such as the sensitivity of the natural capital asset to changes and the reversibility of such changes (NCFA and UN Environment World Conservation Monitoring Centre, 2018) were taken into account here.

These elements have been combined as shown in Table 2-4. We have cited the evidence for our judgements in the next section so that readers may undertake their own alternative assessment if they wish.

Table 2-4 Scoring used to assess the degree of impact/dependence, and the severity of consequences/threat, used to determine materiality

Degree of impact/dependence	Severity of consequences/threats	Materiality
Low	Low	Low
Low	Moderate	Low
Low	High	Moderate
Moderate	Low	Low
Moderate	Moderate	Moderate
Moderate	High	High
High	Low	Moderate
High	Moderate	High
High	High	High

Finally, we have discussed the ways in which a typical forestry company could mitigate the identified risks. We have not included risk mitigation in our materiality assessment, as this will depend on the actions of individual companies.

3. Natural capital risks in Australian forestry

Australia has approximately 3% of the world's forests: 134 million hectares, covering 17% of Australia's land area (ABARES 2018). 98% of this is native forest, with the remainder being commercial plantations and other forest (e.g. non-commercial plantations). The commercial production of wood in Australia is derived from both native forests and plantations. Figure 3-1 shows the spatial distribution of native forests and plantations across Australia. The majority of plantations in Australia are in the east and south-east of the country along with south-west of Western Australia; these also tend to be the areas with native forest most suitable for commercial production.

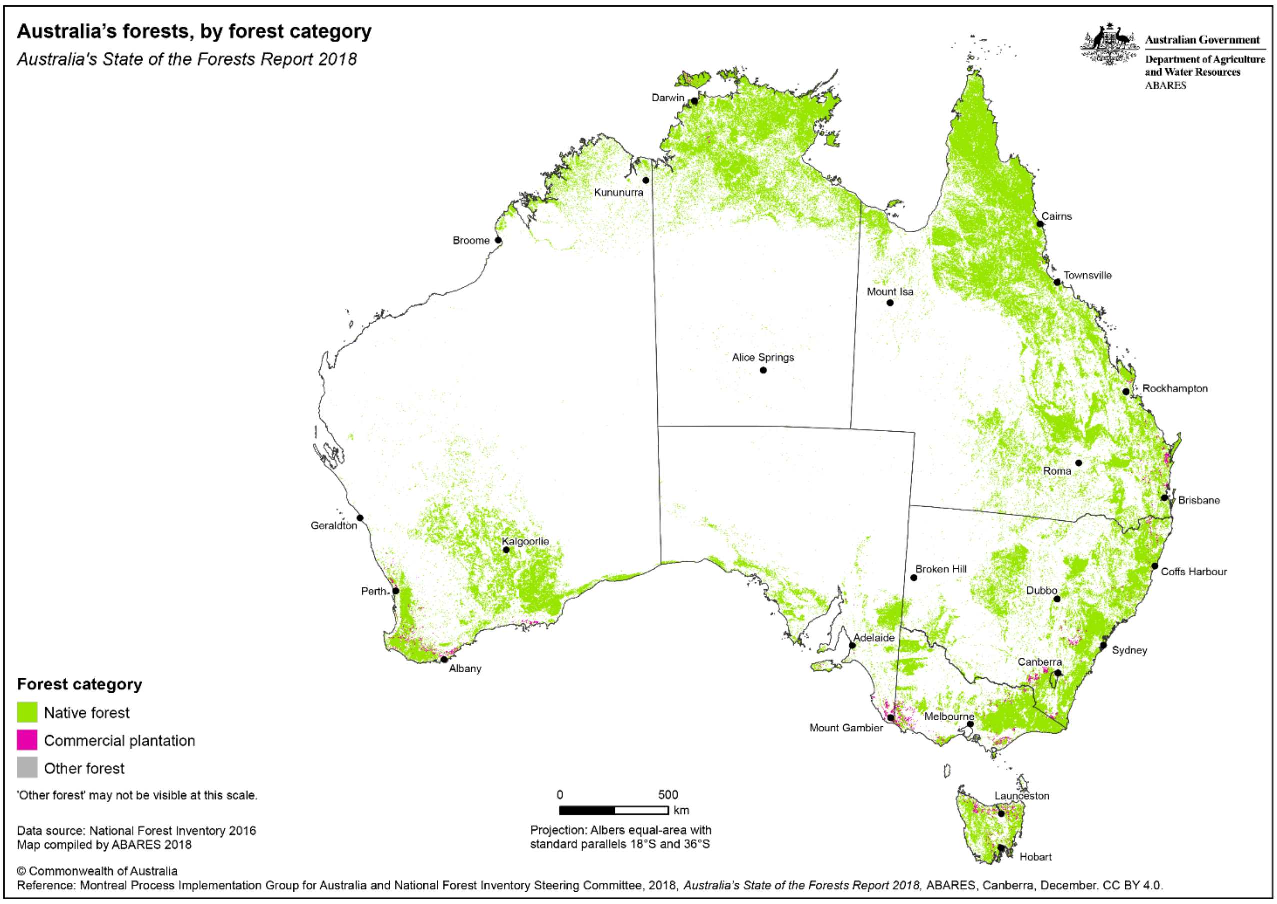


Figure 3-1 Australia's forests, by forest category
Source: (ABARES 2018).

Plantations in Australia total an area of 1.95 million hectares (2014-15), which is 1.5% of Australia's forest area. The plantations comprise softwood species (1 million hectares which are predominantly *Pinus radiata*) and hardwood species (0.9 million hectares which are predominantly eucalypts, with *Eucalyptus globulus* the most common species). 79% of plantations are privately owned and 21% government owned.

The total area of productive native forests available in Australia is approximately 28 million hectares (21% of Australia's forest area). However, a substantial proportion of this is rated as unsuitable for commercial forestry, due to isolation from markets and being financially unviable for harvesting, or due to being managed for non-timber values as part of multiple-use public forests. Once these restrictions and exclusions are accounted for, the remaining harvestable native forest area (2014-15) is approximately 5 million hectares (4% of Australia's forest area).

A range of silvicultural systems are used for forest harvesting. Of the area of multiple-use public native forest harvested over the period 2011–12 to 2015–16, 86% was harvested using selection systems (selection and commercial thinning), 9% by clearfelling systems (clearfelling, fire-salvage clearfelling and intensive silviculture with retention), 5% by shelterwood systems, and 0.2% by variable retention systems (ABARES 2018).

In the next sections, we discuss each of the major risks arising from Australian forestry's operational dependencies and impacts on natural capital, as summarised in Figure 3-2 below.

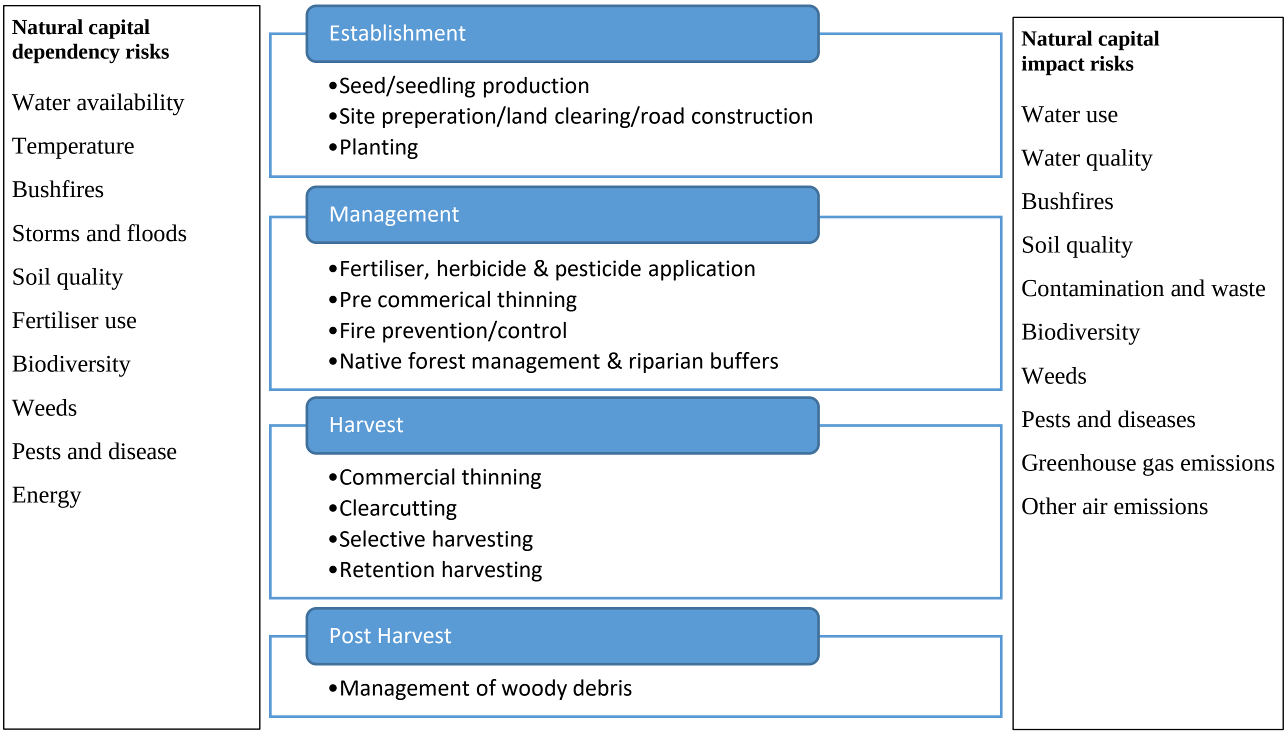


Figure 3-2. Forestry activities and natural capital dependency and impact risks.

3.1 Water availability (dependency risk)

Definition: the risk that rainfall, or groundwater resources, will be insufficient to produce the target volume and quality of harvestable biomass.

Principal pathway: The financial performance of a forestry company is linked to timber revenue, which in turn depends on the volume and quality of harvestable biomass (an ecosystem service) produced per unit land area over a given period of time. Plant available water is a major determinant of productivity and tree survival. Climate change and increased competition for groundwater reserves may change water availability for forestry in future.

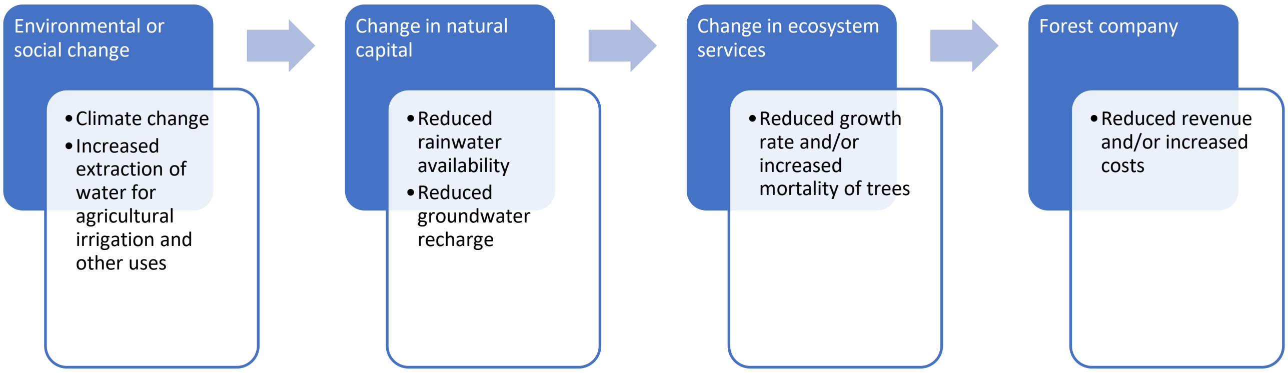


Figure 3-3 Causal pathway describing risks arising from the dependency of forestry companies on water availability

Evidence

Degree of dependency (water availability): In Australia, rainfall is the main source of plant available water for the forestry estate, although access to groundwater is important in some parts of Western Australia and South Australia (Benyon et al. 2006). At regional scales, long-term water availability exerts a strong influence on plant productivity and survival, as demonstrated by correlations between annual precipitation and leaf area index (Ellis and Hatton 2008), which is in turn correlated with net primary productivity. Studies consistently show correlation between leaf area index and long-term rainfall (Myers et al. 1996, Battaglia et al. 1998, Medlyn et al. 2011). This is strongest for native forests in water-limited environments, i.e. environments where potential evaporation is larger than rainfall (climate wetness index < 1). Where rainfall is larger than evaporation, productivity is limited by the availability of energy and there is often no relationship between leaf area index and water availability (Donohue et al. 2007). Water availability can also influence wood quality through its impact on traits such as basic density and microfibril angle (Drew et al. 2009).

Episodic reduced water availability (drought) is a threat to forest productivity and mortality. In short-term or moderate intensity drought, plants control water use by reducing stomatal conductance, thereby decreasing risks to productivity and survival. Medium-term or medium intensity drought can reduce leaf area and biomass allocation leading to losses in forest productivity. Longer-term or high intensity drought can ultimately lead to death of the trees. Mortality related to extreme shortages in water availability has been documented in plantations since the 1960s, primarily at sites with shallow soils close to canopy closure (Battaglia et al. 1998, Pinkard et al. 2014b). For example, extreme drought in the south west of Western Australia has been linked to forest canopy collapse in jarrah forests (74 % of all measured tree stems had dying or recently killed crowns) (Matusick et al. 2013).

Water availability is not determined by climatic conditions alone; other factors that influence it include soil depth, topography, aspect, and soil texture and structure (Battaglia and Williams 1996). Any estimate of survival and productivity impacts based on changes in water availability therefore needs to consider these factors.

Severity of threat (water availability): Changes in precipitation amounts or patterns, and changes in the availability of groundwater reserves are threats to the water that forests depend on. Climate change is already affecting long-term rainfall patterns across Australia. For example, a 15% reduction in rainfall has been observed in southwest Western Australia since the 1970s (Steffen and Hughes 2011), and further changes are projected, with reductions in rainfall predicted for much of southern Australia (CSIRO and Bureau of Meteorology 2018). By the middle of the century, under a high emissions scenario, winter decreases in rainfall in southern Australia are projected to be evident against natural variability. Changes to summer and autumn rainfall are also possible but not certain.

Groundwater resources face threats from reduced recharge due to the combined effects of increasing temperature and changes to precipitation (Earman and Dettinger 2011, Crosbie et al. 2012) as well as increased pressure from extraction for irrigation and other uses (Kløve et al. 2014). In Australia, an assessment of climate change impacts on groundwater resources (Barron et al. 2011) predicts decreases in groundwater recharge across the majority of the west, centre and south of Australia (where the majority of production forests occur), while increases in groundwater recharge are projected across northern Australia and certain areas of eastern Australia. Using a median future climate (Barron et al. 2011) show that 79% of Australia is predicted to experience a reduction in recharge by 2050. Groundwater declines have already caused the degradation of water-dependent ecosystems such as riparian forests in the USA (Stromberg et al. 1996) and floodplain forests in Australia and Europe (Cunningham et al. 2011, Kath et al. 2014, Skiadaresis et al. 2019).

LINKS TO OTHER RISKS	EXPLANATION
Water use (impact risk) **Section 3.2**	• Water availability risk can be affected by competition for resources such as groundwater, and associated water licencing regimes. • Water use risk can be affected by changes in rainfall or groundwater resources and can affect the overall level of water stress within a catchment.
Temperature (dependency risk) **Section 3.4**	• Water availability risk can be confounded by heat waves. In Australia, a number of large-scale mortality events in eucalypt forests have been linked to combined drought and heatwaves (Bates et al. 2008, Mitchell et al. 2014). The combined effect of a drying and warming climate can cause an increase in climate-driven tree mortality (Allen et al. 2010, Allen et al. 2015).
Bushfire (dependency/impact risk) **Section 3.5 and 3.6**	• Bushfire risk (e.g. spread and intensity) can be affected by recent drought-induced die-off due to increased deadwood material and higher near-ground solar radiation (Ruthrof et al. 2016).
Soil quality (dependency/impact risk) **Section 3.8 and 3.9**	• Water availability risk can be affected by the ability of soil to hold moisture; forestry activities can impact on the soil (e.g. causing compaction). • Soil quality risk can be affected by water availability and drought effects.
Weeds (dependency/impact risk) **Section 3.14 and 3.15**	• Water availability risk can be affected by weed competing with trees. • Weed risk (e.g. growth and distribution) just like other plants, can be affected by the availability of water.
Pests and diseases (dependency/impact risk) **Section 3.16 and 3.17**	• Water availability risk can be confounded by pests and diseases. Drought can make trees more susceptible to other stressors such as pests and diseases and vice-versa. The impact of forestry activities on the incidence or impact of pests and diseases can be modified by reduced water availability. Some species, such as stem borers, are attracted to water stressed trees. Other species, such as leaf fungi, require moisture to germinate and hence populations may decline.
Greenhouse gases (impact risk) **Section 3.19**	• Greenhouse gas risk can be affected by water availability. For example, water availability is a key determinant of tree growth and affects the GHG sequestration rate of forests. Droughts have been associated with increased incidence of tree mortality and therefore GHG emissions.

MATERIALITY

SOFTWOOD PLANTATIONS	HIGH

- **Degree of dependency: High**. Water availability is a critical determinant of tree growth and survival.
- **Severity of threats: High.** Rainfall is declining in many plantation areas in Australia, leading to significantly increased water stress. There is a moderate risk of financial impact from gradual change in average rainfall and high risk of financial impact from drought. New plantations may be unable to obtain or afford water allocations in water-stressed areas.

HARDWOOD PLANTATIONS	HIGH

- **Degree of dependency: High**. As for softwood plantations. However, the shorter length of hardwood rotations in Australia provides more opportunities for adaptation, although such adaptations may come at a cost.
- **Severity of threats: High.** As for softwood plantations.

NATIVE FORESTS	HIGH

- **Degree of dependency: High.** As for plantations.
- **Severity of threats: High.** The long rotations mean that native forests are more exposed to both gradual change in average rainfall and drought, with high uncertainty about future conditions.

Risk mitigation options

There are many options for mitigating risks related to water availability:

- Site selection: sites can be selected according to projected mean annual rainfall. Modelling tools are required to assist in making these decisions, given the 10–30 year length of forest rotations.
- Site preparation: fallowing can be performed on drier sites to increase soil water stores prior to planting (Mendham et al. 2011). This is not a routine practice in Australia, although it is being applied in response to second rotation decline issues in *E. globulus* plantations in Western Australia (Pinkard et al. 2014b). There is an opportunity cost associated; site productivity is decreased by the ratio of the fallow period to rotation length (Mendham et al. 2011).
- Species selection: within the current suite of plantation species, *Pinus radiata* is generally more tolerant of water limitations than eucalypt species. *Pinus pinaster* has been substituted for *P. radiata* at drier ends of the range. Within species, at least two *E. globulus* breeding programs have selected for drought resilience, although there has been little field deployment to date (Dutkowski and Potts 2012). While a range of studies have identified potential alternative species for sites with lower water availability, in practical terms there are barriers to overcome related to growing, processing and marketing new species (Bush et al. 2018).
- Nursery management and early establishment: Seedlings can be drought-hardened prior to planting to enhance survival and early growth. Hardening of *P. radiata* involves reducing the shoot size by

around a third prior to planting. Nutritional hardening has proved successful in eucalypt establishment (Close and Beadle 2003). In some regions of southern Australia, weed control is continued for longer on drier sites to reduce competition for resources (Baker et al. 1988). The use of slow release fertilisers can also promote rapid early growth and prolific root development.

- Silviculture: reduced stocking rates can be used to manage survival and productivity in lower rainfall regions (Mendham et al. 2007). This can be applied either at planting, or via thinning. Parts of the industry in Western Australia have adopted lower stocking rates, based on the guide that 800 mm of rainfall can support approximately 800 stems per hectare (White et al. 2009).

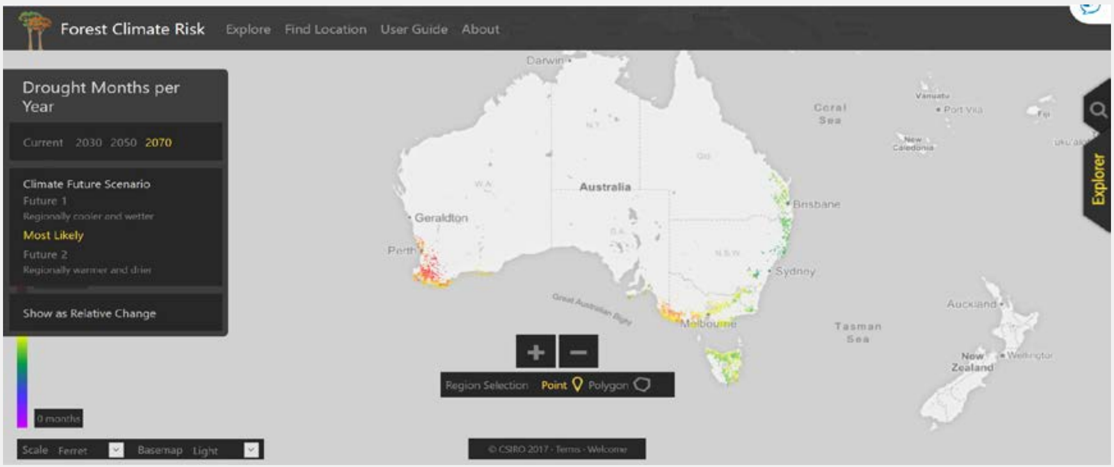
Predicting Future Climate

Future climate cannot simply be extrapolated from past climate. The climate is subject to numerous non-linear processes and future emissions of greenhouse gases must also be considered. Future projections of climate use mathematical representation of the atmosphere and oceans, called general circulation models or global climate models (GCMs). These models typically have a resolution of 200 km and represent features of the atmosphere, such as high- and low-pressure systems, and large-scale oceanic currents and overturning. The coarse spatial scale of GCMs means its use for projecting local and regional features and processes is limited. To provide projections at regional and local scales, dynamic downscaling of GCMs is used (CSIRO and Bureau of Meteorology 2018).

Forest Climate Risk Tool (CSIRO)

The Forest Climate Risk Tool is a mapping and reporting application that provides registered users with climate information based on current and future climate scenarios. The information is relevant for evaluating potential climate risk on forest growth and management. The climate information is mapped across the known spatial extent of the Australian hardwood and softwood plantation areas (Forests of Australia 2013) (excluding areas in the Wet Tropics and Top End regions).

The tool groups numerous indices under Temperature, Rainfall and Drought, and Heatwaves and Fire Danger themes and the climate projections cover the years 2030, 2050 and 2070 for three different Climate Future Scenarios, which can be compared against current climate. The scenarios provide an indication of the range of potential future climate conditions, including a ‘most likely’ scenario.



Drought Months per Year

Current 2030 2050 2070

Climate Future Scenario
Future 1
Regionally cooler and wetter
Most Likely
Future 2
Regionally warmer and drier

Show as Relative Change

Region Selection Point Polygon

Scale Ferret
Basemap Light

https://research.csiro.au/climatesmartagriculture/data-tools/forest-climate-risk-tool/

3.2 Water use (impact risk)

Definition: the risk that water used is non-renewable, extracted beyond its renewal rate, or diverted away from other ecosystems or users (Peters et al. 2010, Ascui and Cojoianu 2019a).[4]

Principal pathway: Establishment of new forests can significantly increase evapotranspiration of water relative to other non-forest land uses. This can reduce the rate of groundwater recharge and the quantity of surface water runoff, thus impacting other users of that water. There is potential for new plantations to be unable to obtain the necessary water access entitlements in over-allocated or water stressed catchments.

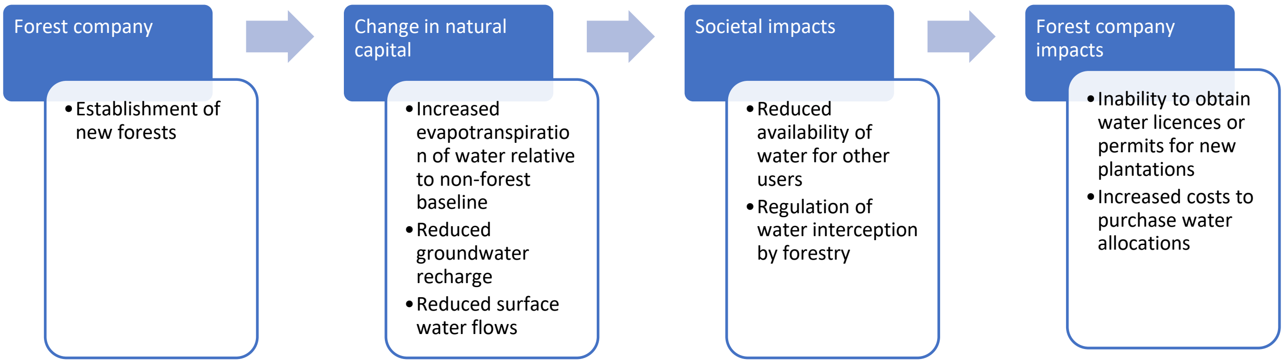


Figure 3-4 Causal pathway describing risks arising from the impacts of forestry companies on water use

Evidence

Degree of impact (water use): All forests use water during growth: tree growth, leaf area and tree water use are strongly related, such that a highly productive forest will use more water. Trees extract soil moisture through their extensive root systems and release it to the atmosphere through evapotranspiration. This water is then not available for groundwater recharge (Crosbie et al. 2010) and/or surface water flows, and can therefore be considered to be diverted from other ecosystem uses (to the extent that there is any change from previous water yield, or availability for other users). Most of the relevant soil moisture derives from rainfall, but trees can also directly extract groundwater where water tables are shallow (Harvey 2007). Evapotranspiration is limited by the amount of energy to drive the process and is also limited by the availability of water. Where there is ample water availability, such as where there is shallow and fresh groundwater, evapotranspiration is limited by energy. For most Australian forests, evapotranspiration is limited by water availability (Prosser and Walker 2009).

Water use by existing forests most likely represents a continuation of the current situation, although higher temperature future scenarios may result in more water use in some situations. There may also be variations in water use across the rotation in production forests, although these will tend to average out over larger areas and over time. New plantations, on the other hand, tend to use significantly more water than replaced land uses such as dryland agriculture, due to their high productivity and evapotranspiration potential (Harvey 2007). This change represents an impact on natural capital (surface and sub-surface water) that can in turn affect other water users in the catchment. However, the interactions between new plantations and catchment water availability are complex. There have

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[4] 'Non-renewable' water is also known as 'fossil' water and refers to groundwater resources that have a negligible rate of renewal (recharge) over human timescales - http://www.fao.org/3/Y4473E/y4473e06.htm (accessed 9 November 2020).

been numerous reviews of the impacts of afforestation on catchment water availability conducted over many years (Calder 1998, Zhang et al. 2001, Benyon et al. 2006, Polglase and Benyon 2009, Filoso et al. 2017). The most recent global systematic review by Filoso et al. (2017) found that in 80% of the studies reviewed the impact of afforestation on water yield was negative, while 6% were positive and the remainder were unclear. Of the studies that reported impacts on low flows, 63% found a negative impact, although the authors acknowledge that the data set of publications reporting impacts on low flows was small by comparison. In the same review, 67% of the studies that reported impacts on groundwater reported a decline in groundwater levels associated with afforestation. For example, a modelling study in South Australia estimated that water extraction from aquifers was in the order of 1.8 ML/ha/year for hardwood plantations and 1.6 ML/ha/year for softwood plantations, and recharge to aquifers was reduced by 83% compared to dryland agriculture recharge rates (Harvey 2007).

While there is general agreement that afforestation decreases water yield (overall, at low flows, and in terms of groundwater), the magnitude of the impacts is complicated by a number of factors including species, age, water availability, ecohydrological context, landscape setting and area of reafforestation, making it difficult to generalise the magnitude of likely impacts with any precision. Over longer time frames (decades) water yield may recover as stands develop and mature (Vertessy et al. 1996). However, it is unlikely that this longer-term recovery in water yield would be observed in areas predominantly occupied by plantations, as these ‘short rotation’ situations are managed in a manner that minimises the later aged declines in productivity that are observed in older stands.

Water flows downstream may also be vary according to the stage of the rotation. For example, lower flows at mid to late rotation followed by increased flows after harvesting. There is also evidence that forests can provide positive ecosystem services to downstream communities in the form of flood mitigation and improved water quality (see sections 3.7 and 3.3 respectively). For example, of the 43 studies included in the review that addressed peak flows, 82% reported a decline in peak flows and flooding frequency (Filoso et al. 2017). This response may be related to the increased infiltration rates reported by 83% of the studies, which could, over longer periods, also lead to improved groundwater recharge – however, the science is currently highly uncertain on this potential benefit (Filoso et al. 2017).

Severity of consequences (water use): Water use in Australia is regulated by the Commonwealth and state governments under the 2004 Intergovernmental Agreement on a National Water Initiative (COAG 2004). Under the National Water Initiative (NWI), forestry is deemed to be a water intercepting activity requiring water access licensing for additional interception activities above certain threshold sizes, in highly allocated catchments in particular. Implementation of the NWI varies by state and territory. For example, in South Australia, the Natural Resources Management (Commercial Forests) Amendment Act 2011 provides a forest water licencing system that closely mirrors general water licences and permits.[5] Under this legislation, depending on circumstances within specific catchments, a plantation forest owner may be required to apply either for a water licence that provides water allocations that can be traded with other licensed water users, or a water-affecting activity permit, which can set conditions on the extent and location of permitted forestry activities. In general, existing plantations are likely to be granted water licences sufficient to continue their existing activities, but expansions and new plantations may be restricted in their permitted scope (Government of South Australia 2009). Western Australia published plantation forestry and water management guidelines in 2009 (Government of Western Australia: Department of Water 2009),

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[5] https://www.environment.sa.gov.au/topics/water/water-for-the-economy/water-for-commercial-forestry (accessed 2 April 2020).

which flags the potential for licencing plantation water use but this has not been implemented yet. In general, therefore, there is a possibility of new or expanded plantations being unable to obtain regulatory approval to proceed, or facing higher costs in the form of water rights, but this risk varies across and within states and is only likely to apply in water-stressed catchments. Regulations would not apply retrospectively, thus mitigating any financial impact, although land purchased in the absence of a licence or permit could potentially be stranded. Beyond this, there is also a potential risk of loss of 'social licence' due to community perceptions that forestry may be reducing water availability for others.

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Water availability risk can be affected by competition for resources such as groundwater, and associated water licencing regimes. • Water use risk can be affected by changes in rainfall or groundwater resources and can affect the overall level of water stress within a catchment.
Temperature (dependency risk) Section 3.4	• Water use risk can be affected by high temperatures for example through increased evapotranspiration of water (Prosser and Walker 2009).

MATERIALITY

SOFTWOOD PLANTATIONS	MODERATE

- **Degree of impact: Moderate** for new plantations in water stressed catchments. **Low** for existing plantations and new plantations in non-water stressed catchments.
- **Severity of consequences: Moderate** for new plantations in water stressed catchments. **Low** for existing plantations and new plantations in non-water stressed catchments.

HARDWOOD PLANTATIONS	MODERATE

- **Degree of impact:** As for softwoods plantations.
- **Severity of consequences:** As for softwoods plantations.

NATIVE FORESTS	LOW

- **Degree of impact: Low.** In Australia, native forests are predominantly a continuation of existing land use, and their water use is unlikely to change significantly in future.
- **Severity of consequences: Low.** A regulatory response is unlikely, but there is a possible risk associated with community perceptions of water diversion, for production forests only.

Risk mitigation options

Timing of thinning and harvesting operations can be managed to maintain or improve catchment water flows. For example, forest thinning is used as a tool in catchment management areas to improve water yields (Bari and Ruprecht 2003). Responses to thinning are likely to be short term as the remaining trees grow to fully occupy the site (White et al. 2009).

Limiting harvesting to small areas within catchments helps to minimise yield impacts as forests recover (Almeida et al. 2016).

Co-management of water between users has proven to be effective in agricultural catchments (Ellison et al. 2019), resulting in improved understanding between users of their needs and building constructive decision-making outcomes.

3.3 Water quality (impact risk)

Definition: the risk that forestry activities negatively affects the quality of surface or sub-surface water (Ascui and Cojoianu 2019a).

Principal pathway: Forestry activities can affect water quality in two main ways—through physical disturbance of the land (both on-site, such as through site preparation, harvesting and fire, and off-site through the creation of roads and landings) which can lead to increased erosion and run-off into waterways; and through the use of chemicals (fertilisers, pesticides and herbicides) which can leach into nearby water courses or enter directly where these are aerially applied or are followed closely by significant rainfall events. There is potential for these impacts to be more tightly regulated and/or socially unacceptable in future, which could increase operating costs for forestry companies and/or decrease revenues due to restricted market access.

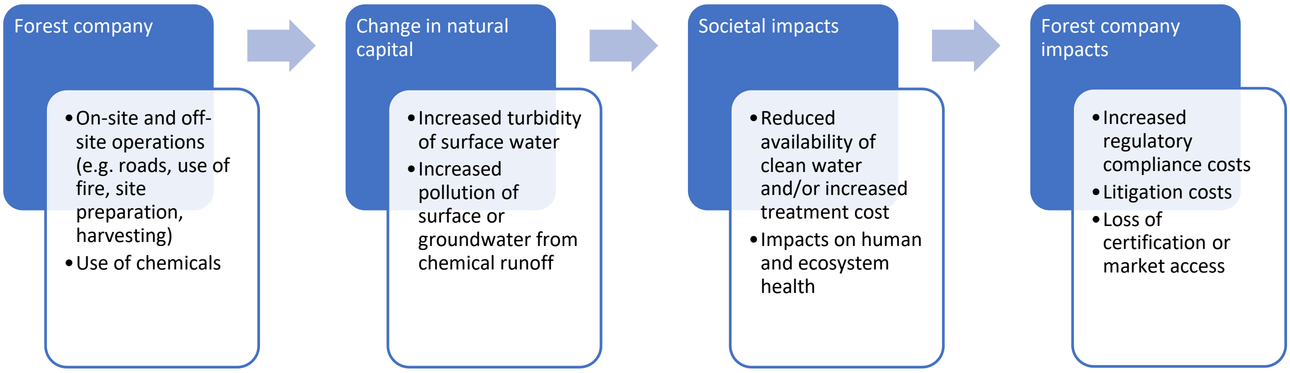

Figure 3-5 Causal pathway describing risks arising from the impacts of forestry companies on water quality

Evidence

***Degree of impact* (water quality):** Forestry activities require the construction and maintenance of an extensive network of roads, landings, bridges and culverts. As many forestry roads are unsealed, there is potential for increased erosion, leading to adverse impacts on water quality (Forsyth et al. 2006). The magnitude of any potential impact is dependent on a number of factors including the type of road and construction techniques, level of traffic and soil texture, slope etc (Boston 2016). Site preparation and harvesting are periods of higher risk associated with these activities as these tend to be associated with higher management intensity and traffic loads (Forsyth et al. 2006, Baillie and Neary 2015). The largest potential for water pollution associated with this pathway is associated with poor construction techniques, roads on steep slopes or soils with high erosion risk, and stream crossings (Boston 2016). Evidence for these impacts in Australia is limited to a few studies which have demonstrated increases in turbidity and suspended solids associated with these activities (Lane and Sheridan 2002). Increases in turbidity and suspended solids can affect water quality by altering natural temperature regimes, reducing the level of dissolved oxygen, increasing nutrient loads and reducing the level of light penetrating the water. In general, there is a lack of long-term monitoring to assess the magnitude of these impacts from forestry road-related activities on water quality. In a review of water quality in New Zealand forests, Baillie and Neary (2015) suggest that impacts are likely to be low and short term in nature.

On-site activities such as site preparation, harvesting and burning also have the potential to increase erosion. Existing studies were short term in nature and equivocal in the direction and magnitude of impacts. Best management practices appear to be effective at mitigating impacts associated with these activities (Webb et al. 2007).

The second major pathway that can potentially give rise to impacts on water quality is the use of synthetic chemicals, particularly fertilisers, herbicides and pesticides. The use of these chemicals is important for maintaining productivity, but there are risks associated with the leaching and leaking of these chemicals into waterways. While there is a large body of literature associated with agricultural settings, the body of literature pertaining directly to forestry is smaller (Baillie and Neary 2015). There is general agreement that the use of these chemicals can lead to short-term increases in concentrations of the active ingredients in water, but Neary et al. (1993) conclude that typical low concentrations and short residence times do not pose a significant risk to water quality.

Overall, the risk to water quality associated with well-managed forestry activities is generally thought to be low. Furthermore, conversion of agricultural land to forestry can lead to improvements in water quality as inputs of sediments and chemicals are lower under this land use (Baillie and Neary 2015).

Severity of consequences (water quality): Existing codes of practice in Australia, e.g. Tasmania's Forest Practices Code 2015 (Forest Practices Authority 2015) are designed to promote the protection of water quality by aiming to minimise the disturbance to water courses and riparian zones. The likelihood of substantially increased costs of regulatory compliance is considered to be low, due to the low level of impacts and available mitigation options. Nevertheless, recent litigation in the US associated with pollutant inputs into waterways associated with forestry roads highlights ongoing community concerns with regard to this pathway (Boston 2016).

LINKS TO OTHER RISKS	EXPLANATION
Bushfires (impact risk) Section 3.6	• Water quality risk can be affected by bushfires, for example, when post fire rainfall washes contaminants into waterways and reservoirs.
Storms and floods (dependency risk) Section 3.7	• Water quality risks from forestry activities can be exacerbated by storms, with the magnitude of impacts dependent on factors such as road construction techniques, soil texture and slope (Boston 2016).
Soil quality (dependency/impact risk) Section 3.9	• Water quality risks can be affected by soil erosion and soil degradation (Lane and Sheridan 2002, Aust and Blinn 2004). Major soil disturbance activities such as the establishment of roads and operational infrastructure can cause localised changes in overland flow resulting in erosion (Grigal, 2000), with associated risks of sedimentation to waterways.
Fertiliser (dependency risk) Section 3.10	• Water quality risk can be affected through potential runoff of fertilisers into waterways after application.
Contamination and waste (impact risk) Section 3.11	• Water quality risks can be affected by synthetic chemicals leaching into waterways (Neary et al. (1993).

MATERIALITY	
SOFTWOOD PLANTATIONS	**LOW**
• **Degree of impact: Low.** Evidence for significant impacts is limited and best management practices appear to be effective at minimising impacts. • **Severity of consequences**: **Low.** The likelihood of substantially increased costs of regulatory compliance is considered to be low.	
HARDWOOD PLANTATIONS	**LOW**
• **Degree of impact: Low.** As for softwood plantations. • **Severity of consequences**: **Low.** As for softwood plantations.	
NATIVE FORESTS	**LOW**
• **Degree of impact: Low.** As for softwood plantations. • **Severity of consequences**: **Low.** As for softwood plantations.	

Risk mitigation options

Mitigation options are well-documented in regional Forest Practices Codes. They include providing adequate drainage and watercourse crossings during infrastructure development; planning harvesting operations to minimise soil erosion, damage to watercourses or damage to riparian buffer zones, and management of contaminants and rubbish. Riparian buffers also appear to be effective in mitigating water quality impacts (Hickey and Doran 2004).

3.4 Temperature (dependency risk)

Definition: the risk of lower productivity, tree mortality, and increased costs due to exposure to changes in average temperatures, or temperature extremes (Ascui and Cojoianu 2019a).

Principal pathway: The financial performance of a forestry company is linked to timber revenue, which in turn depends on the volume and quality of harvestable biomass (an ecosystem service) produced per unit land area over a given period, and the capacity to perform forest operations to manage the forest. Temperature is a major determinant of tree productivity and survival and may also impact wood quality. Climate change is expected to shift average temperatures upwards and increase the frequency and severity of high temperature events potentially exposing forestry to reduced productivity and tree mortality.

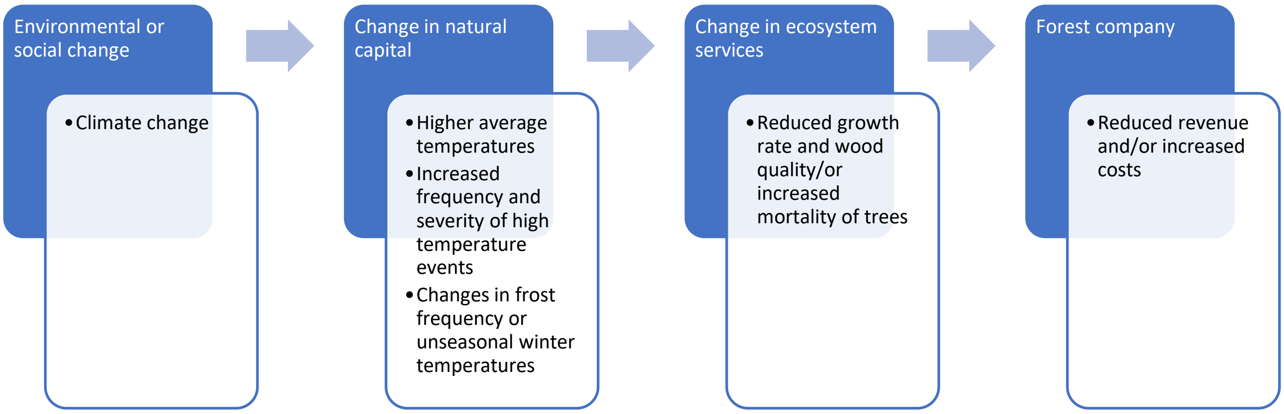

Figure 3-6 Causal pathway describing risks arising from the dependency of forestry companies on temperature

Evidence

Degree of dependency (temperature): Temperature is a major factor controlling tree growth rates (Kirschbaum et al. 2012). The effect of temperature varies according the tree species and whether the current temperature range of a species is above or below its optimal temperature, and its capacity to acclimatise. Temperatures outside the optimum range for tree growth performance can result in decreased production (Battaglia et al. 2009), and if temperatures move outside a species' suitable range then growing that species becomes unviable.

In Australia, common plantation tree species are grown at broad temperature ranges and evidence from around the world suggests that many species can tolerate conditions somewhat different from those experienced within their natural distributions (Booth 2013, Booth et al. 2015). *Pinus radiata* is tolerant of a broad range of temperatures, growing in climates where the mean maximum temperature of the hottest month ranges from 13°C to 29°C.[6] *Pinus radiata* is also tolerant to frost, with studies suggesting trees may tolerate temperatures to -17°C. *Eucalyptus globulus* tolerance of temperature increases may be more limited, and evidence shows limitations to its temperature acclimation of photosynthesis in summer (Crous et al. 2013). A number of native eucalypt species in Australia occur over small ranges of annual mean temperature: for example, half of all native species occur over temperature ranges of less than 3°C (Hughes et al. 1996). Research has shown that rising temperatures may result in an overall decline in growth of native eucalypt species (Bowman et al. 2014). However, native species have also been shown to acclimate to a range of different temperatures with

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[6] https://www.cabi.org/isc/datasheet/41699 (accessed 1 April 2020)

photosynthesis rates correlated to the temperature ranges in which the trees grow (see Cunningham and Read (2002).

The frequency and severity of high temperature weather events (heat waves) have a strong influence on species survival and growth (Allen et al. 2010). Evidence shows that during the growing season, the impact of heat waves on growth can be significantly greater than heat accumulated evenly over the same period (Bauweraerts et al. 2014, Teskey et al. 2015). Results from a recent paper using Australian and global case studies (O'Sullivan et al. 2017) indicate that upper canopy leaves of many trees in mid-latitudes operate close to their metabolic thermal limits during heat-wave events. Species such as *E. globulus* can be damaged or killed by short term exposure to temperatures between 40-50°C (Stephens et al. 2012) and by longer-term exposure to temperatures as low as 35-40°C (Pinkard and Bruce 2011). In 2019 alone, 110,000 ha of forest in Germany, with a replanting cost of EUR660 million, were destroyed by a combination of high temperatures and drought, leaving weakened trees vulnerable to storms and pests such as bark beetle (Buck 2019).

Wood properties are also affected by temperature (Drew et al. 2017). In general, rising temperature tends to increase wood density, although this is not a universal response (Downes et al. 2013). Using process-based modelling to study the potential effects of climate change on wood density, Drew and Bruce (2013) demonstrated that wood density changes depend on whether the growth is currently limited by temperature and the combination of changes in temperature, rainfall and CO_2. As an example, they showed that at sites where growth is limited by low temperature, increases in temperature and decreases in rainfall would result in a moderate increase in stand volume and a large increase in wood density. Increases in wood density could potentially be beneficial for forestry companies and there could be the possibility of new products or processing options becoming viable (Drew et al. 2017).

Cold temperature extremes can also be a threat to tree growth and survival in Australia. Frost currently restricts the distribution of plantation species such as *E. globulus* at the coldest ends of their range. Increases in night-time temperatures and reduced frost frequency in future, due to climate change, could increase the potential distribution of these species. Warmer temperatures, particularly in winter, may promote growth through increased length of the growing season (Booth et al. 2010), higher rates of photosynthesis (Hyvönen et al. 2007) and through increased nitrogen mineralisation rates (thereby improve nutrient supply) (Battaglia and Bruce 2017). However, there is also evidence that warmer temperatures can lead to reduced frost hardening in trees (Woldendorp et al. 2008), and that increasing atmospheric CO_2 may also increase frost sensitivity in eucalypts (Barker et al. 2005).

High temperatures can also restrict a range of forestry operations. Concerns for worker health and fire risk mean that companies restrict access to the forests they manage during periods of high temperatures. This can be costly to businesses in terms of lost days and interruptions to operational schedules.

Severity of threat (temperature): In Australia, there is very high confidence from global climate models that average, maximum and minimum temperatures will continue to increase in all seasons (CSIRO and Bureau of Meteorology 2018). Extreme hot days and warm spells are also projected to increase. This includes substantial increases in the temperature reached on hot days, the frequency of hot days, and the duration of warm spells. Increases in dry summers and heat waves are likely to exacerbate heat stress in trees into the future (Steffen 2009b, CSIRO and Bureau of Meteorology 2015, Steffen 2015). For cold temperature extremes, fewer frosts are projected. As the century progresses frost-risk days (minimum temperatures under 2 °C) are expected to decrease but decadal and regional variability is also projected to increase (CSIRO and Bureau of Meteorology 2018).

Modelling climate change effects on the Australian plantation estate

Pinkard et al. (2014b) analysed the likely effects of climatic change on Australia’s plantation estate for 2030 and 2050 using the process-based model CABALA. Simulations for different assumptions, for example, different photosynthesis responses to elevated CO_2, and for projected climatic conditions were run for major plantation regions across Australia. Results showed strong regional differences for plantations:

- Some regions of the *P. Radiata* and *E. globulus* estates may show decreased productivity while other regions may show increased productivity, with the response strongly determined by local conditions of soil depth and fertility.
- Cold wet sites (for example plantations in the highlands of Victoria) where nutrients are limited may see an additional growth response due to increased nitrogen mineralisation under warmer temperatures.
- Overall, the model predictions are highly sensitive to the responsiveness of plantation species to elevated CO_2.
- In warm dry regions there may be a reduction in survival and in cold environments, survival generally improves in response to warmer temperatures.
- Areas at the dry margins of the estate are vulnerable and in the worst instances look highly likely to fail.

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Water availability risk can be confounded by heat waves. In Australia, a number of large-scale mortality events in eucalypt forests have been linked to combined drought and heatwaves (Bates et al. 2008, Mitchell et al. 2014). The combined effect of a drying and warming climate can cause an increase in climate-driven tree mortality (Allen et al. 2010, Allen et al. 2015).
Water use (impact risk) Section 3.2	• Water use risk can be affected by high temperatures for example through increased evapotranspiration of water (Prosser and Walker 2009).
Bushfires (dependency/impact risk) Sections 3.5 and 3.6	• Temperature risk and fire risk interact. Extreme high temperatures can increase fuel dryness and changing the supply of fine fuel (leaf litter) (Clarke et al. 2016).
Soil quality (dependency/impact risk) Section 3.8 and 3.9	• Soil quality risk can be affected by changing temperatures, for example, potentially increasing the loss of soil organic carbon (Davidson and Janssens 2006).
Biodiversity (dependency/impact risk) Section 3.12 and 3.13	• Biodiversity risk can be affected by changes in temperature. For example, it can alter phenological processes, such as flowering, fruiting (Beaumont et al. 2015, Rawal et al. 2015b, a) and seed set, and other important life-cycle events, such as germination and early growth.
Pests and diseases (dependency/impact risk) Section 3.16 and 3.17	• Pests and disease risk can be affected by changes in temperature and extreme high temperatures can affect the survival and spread of insect and fungal species.
Greenhouse gas (impact risk) Section 3.19	• Greenhouse gas risk can be affected by temperature. For example, temperature is a factor in the greenhouse gas sequestration rate of forests.

MATERIALITY

SOFTWOOD PLANTATIONS **HIGH**

- **Degree of dependency: High.** High temperature weather events (heat waves) have a strong influence on species survival and growth and make this a high material risk. Cold temperature extremes can also be a threat to tree growth and survival in Australia.
- **Severity of threats: High.** Temperatures are increasing with climate change and heatwaves have the potential to cause significant losses across an estate, although uncertainty in the species response remains high. Shifts in mean temperatures will influence where plantations can be grown economically; more frequent/intense/longer heatwave events will affect productivity, survival and wood properties.

HARDWOOD PLANTATIONS **HIGH**

- **Degree of dependency: High.** As for softwood plantations.
- **Severity of threats: High.** As for softwood plantations.

NATIVE FORESTS **HIGH**

- **Degree of dependency: High.** As for softwood plantations.
- **Severity of threats: High.** As for softwood plantations.

Risk mitigation options

Mitigation options for managing extreme temperatures are limited. They include:

- *Site selection:* site selection for temperature may be restricted in certain regions where the temperature is fairly uniform, however, sites at higher altitudes or more poleward may offer some protection against temperature extremes.
- *Genetic selection for heat tolerance*: Improving the thermotolerance of valuable genotypes has thus far proven difficult (Neale and Kremer 2011). While there is research underway to understand genetic variation in heat tolerance, it will be a number of years before field deployment is likely.
- *Species selection*: Alternative species have been investigated, in particular for hotter and drier parts of the forestry estate. There are a number of hardwood species such as *E. smithii*, *E. cladocalyx*, *Corymbia maculata*, *E. occidentalis*, *E. tricarpa*, *E. muelleriana* that have been investigated for the 400-600 mm mean annual rainfall zone. However, most of these hardwood species either do not have sufficient growth rates or the required wood properties. For softwoods, *P. pinaster* has been grown (and selected and bred) for the low rainfall zone in Western Australia and South Australia (Battaglia et al. 2009).

3.5 Bushfires (dependency risk)

Definition: the risk of lower productivity, tree mortality, and increased costs due to exposure to bushfires.

Principal pathway: Bushfires can be considered an example of an ‘ecosystem disservice’ resulting from the interaction of biomass production (fuel load) and extreme weather conditions (e.g. low humidity, high temperatures, strong winds and lightning). Bushfires can result in financially significant losses of standing timber, carbon and biodiversity in forests, as well as damage to buildings and other assets, and loss of life. Fire can change soil characteristics which may result in increased erosion due to loss of ground cover and increased run-off, which in turn can affect downstream water quality. Fires can also impact others through smoke and dust storms. However, less extreme managed fires can be beneficial for regeneration of native forests, and reduction of fuel load. Climate change has the potential to increase the frequency, severity and/or duration of bushfires in future.

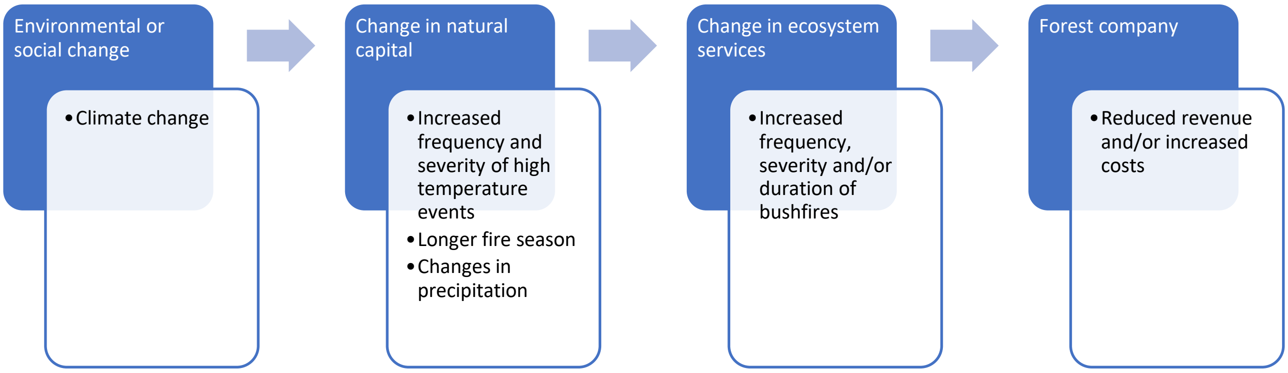

Figure 3-7 Causal pathway describing risks arising from the dependency of forestry companies on bushfires

Evidence

Degree of dependency (bushfires): Forestry companies can be very significantly affected by bushfires. The bushfires of 2019/2020 in Australia burned around 5.8 million ha of forest in NSW and Victoria alone, equating to 21% of Australia’s total temperate forest biome, well above the 2% burnt in a typical fire season (Boer et al. 2020). In NSW approximately 890,000 hectares of native forests and 65,000 hectares of plantations were affected by fire, about half the State Forest estate.[7] Kangaroo Island Plantation Timbers, a forestry company listed on the Australian Stock Exchange, suffered damage to 95% of its estate, insured at a book value of A$115 million but estimated by the industry to have been worth up to A$800-900 million, including independent growers.[8]

The type of forest and severity of bushfires determines the recovery or regeneration actions, and their associated cost. In general, plantations damaged by fire must be cleared completely in order to be re-planted (thus incurring both clearing and re-planting costs) whereas native forests usually regenerate naturally. Native fire-tolerant species have a good chance of recovery where fire has not been too intense. In these areas, trees may withstand the fire and areas may quickly regenerate. In higher fire intensity areas, even fire-tolerant species may die. Softwood plantations affected by fire can still be

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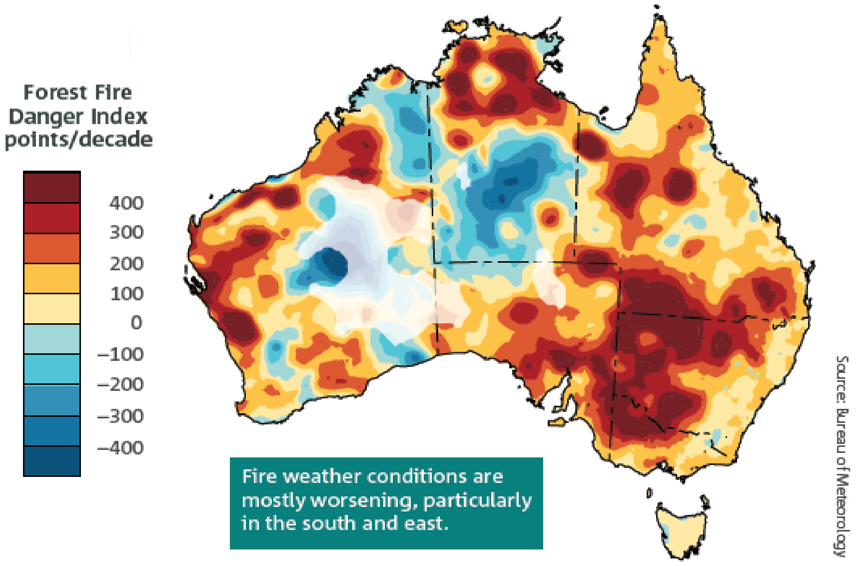
[7] https://www.forestrycorporation.com.au/operations/fire-management/fire-impact-of-2019-20 (accessed 25 February 2020)

[8] https://www.asx.com.au/asx/share-price-research/company/KPT and https://www.abc.net.au/news/2020-02-02/kangaroo-island-sheep-stock-timber-destroyed-in-bushfires/11917220 (accessed 16 March 2020).

harvested (as long as the fire was not too intense) for 12 months or more after a fire[9]; hardwood plantations can be salvaged for up to two years after a fire, and native forests can be selectively harvested.[10] These time pressures can mean that the harvested timber exceeds the capacity of local mills or ports and thus cannot find a market, whilst a glut in supply may also drive down timber prices. Recently burnt forests also pose safety risks to forest workers, and managing these may further increase costs (IFA 2020). Post-fire logging has also been linked to negative biodiversity outcomes (Lindenmayer et al. 2004, Thorn et al. 2018).

Severity of threat (bushfires): High fire risk days have been increasing in frequency over large parts of Australia over the last 40 years Figure 3-8. In Australia, the annual number of hot days (above 35°C) and very hot days (above 40°C) has increased strongly over most areas since 1950. Heatwaves are also lasting longer, reaching higher maximum temperatures and occurring more frequently over many regions of Australia (Perkins-Kirkpatrick et al. 2016). Cool season (April to October) rainfall has decreased in large areas of southern Australia which can result in drier fuel going into the fire season. Since the 1970s, there has been a lengthening of the fire season across large parts of Australia, particularly in southern and eastern regions. The lengthening fire seasons are reducing opportunities for fuel reduction burning (Matthews et al. 2012, Ximenes et al. 2017).



Fire weather conditions are mostly worsening, particularly in the south and east.

Source: Bureau of Meteorology

Figure 3-8 Trends in Australian forest fire danger index between 1978 and 2017.

Source: (CSIRO and Bureau of Meteorology 2018). 1978 to 2017 annual sums of forest fire danger index across Australia presented as decadal trends with red representing increases and blue decreases in the forest fire danger index.

The Forest Fire Danger Index (FFDI) measures the degree of fire danger in Australian forests through combining a record of dryness with temperature, humidity and windspeed conditions to produce an indicator of the ease of ignition, intensity and potential spread of fire. FFDI values are expected to increase substantially by the end of the 21st century (Clarke et al. 2011, Clarke et al. 2016). In particular, an increase in cumulative FFDI (calculated as the sum of the daily maximum FFDI across a year) highlights the heightened potential for incidence and severity of bushfires. Additionally, the

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[9] https://www.forestrycorporation.com.au/operations/fire-management/2020-bushfire-recovery (accessed 25 March 2020).

[10] https://www.smh.com.au/national/massive-salvage-effort-for-bushfire-burnt-timber-a-race-against-time-20200122-p53tli.html (accessed 16 March 2020).

number of severe fire weather days and severe fires is predicted to increase (CSIRO and Bureau of Meteorology 2018). Studies have highlighted the limitations in predicting extreme bushfires using traditional fire danger indices (Hasson et al. 2008, Wood et al. 2008, Hasson et al. 2009, Sharples et al. 2010, Sharples et al. 2016). An alternative method used to predict extreme events is to instead model the strong, deep cold fronts that have been associated with extreme fire events over the last 40 years in Australia. Hasson et al. (2009) show an increase in the occurrence of these deep cold fronts over the 21st century, further supporting the potential for increased frequency of extreme bushfire events.

The El Niño Southern Oscillation (ENSO) is a key mode of variability that affects Australia. Drier conditions and more bushfire events occur on average in El Niño years (Williams and Karoly 1999). Rainfall deficits during El Niño events may become stronger (Power et al. 2013), and this may lead to greater fire risks. Indeed, Mariani et al. (2016) identify a significant relationship between El Niño years and both fire frequency and area burnt in southeast Australia. By the mid- to late twenty-first century, the projections include an intensification of El-Niño-driven drying in the western Pacific Ocean including Australia (Power et al. 2013). Similarly, many large fires are preconditioned by positive Indian Ocean Dipole (IOD) events (Cai et al. 2009). A warmer climate is expected to lead to more positive IOD events and this may result in an increase in the conditions suitable for fires in many regions of southeastern Australia and Tasmania (Cai et al. 2009).

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Bushfire risk (e.g. spread and intensity) can be affected by recent drought-induced die-off due to increased deadwood material and higher near-ground solar radiation (Ruthrof et al. 2016).
Water quality (impact risk) Section 3.3	• Water quality risk can be affected by bushfires, for example, when post fire rainfall washes contaminants into waterways and reservoirs.
Temperature (Dependency risk) Section 3.4	• Temperature risk and fire risk interact. Extreme high temperatures can increase fuel dryness and changing the supply of fine fuel (leaf litter) (Clarke et al. 2016).
Storms and floods (dependency risk) Section 3.7	• Bushfire risk can be affected storm conditions such as wind and lightning and extreme fire events are associated with strong, deep cold fronts.
Soil quality (dependency/impact risk) Section 3.8	• Soil quality risk is affected by fire, as shown by changes to soil nutrients and erosion post fire.

Biodiversity (dependency/impact risk) Section 3.12 and 3.13	• Biodiversity risk and bushfire risk interact. For example, Fires can affect forest biodiversity and forest functioning. In addition, harvest residues provide fuel for bushfires and quick microbial decomposition of that residue can reduce fire risk. Transitions to alternative vegetation states/structures could also result in a positive flammability feedback (Coppoletta et al. 2016, Tepley et al. 2018, Burton et al. 2019).
Weeds (dependency/impact risk) Section 3.14 and 3.15	• Weed risk can interact with bushfire risk. For example, some weeds are particularly flammable. There is a risk that soil disturbance associated bushfire will promote weed establishment.
Pests and diseases (dependency/impact risk) Section 3.16 and 3.17	• Pests and diseases risk interacts with bushfire risk. For example, pests and disease tree mortality can increase the fire risk, and in addition, fire can damage trees and make they more susceptible to pests and diseases.
Greenhouse gases (impact risk) Section 3.19	• Greenhouse gas risk can be affected by fire from the significant greenhouse gas emissions that are associated with fires.
Other air emissions (impact risk) Section 3.20	• Air emission risk can be affected by fire. For example, from the emissions of particulates and other air pollutants in smoke and dust from burnt areas.

MATERIALITY

SOFTWOOD PLANTATIONS	**HIGH**

- **Degree of dependency**: **High**. At the extreme, bushfires can cause total losses of all types of forestry assets and incur additional clearing and replanting costs. There are also considerable management and control costs.
- **Severity of threat**: **High**. All indications are that fire risk is increasing.

HARDWOOD PLANTATIONS	**HIGH**

- **Degree of dependency**: **High**. As for softwood plantations
- **Severity of threat**: **High**. As for softwood plantations

NATIVE FORESTS	**HIGH**

- **Degree of dependency**: **High**. As for softwood plantations
- **Severity of threat**: **High**. As for softwood plantations

Risk mitigation options

Mitigation options for managing bushfire are widely practiced and include:

- *Firebreaks and buffers*: Firebreaks are gaps in vegetation that act as a barrier to slow or stop the progress of bushfires. Buffers are treeless areas used to protect populated areas and assets.
- *Prescribed burning*: managing the fuel loads in forests through prescribed burning is common for native eucalypt forests. For the softwood *Pinus radiata*, prescribed burning is not commonly used because it is a fire-sensitive species that can be killed by moderate-intensity fires (Bartlett 2012).
- *Mechanical fuel load reduction*: Mechanical fuel load reduction is a way of managing fuel loads and is more common in other parts of the world, including the USA. Management through mechanical fuel load reduction can refer to thinning trees and is a method for creating fire breaks. Mechanical fuel load reduction may be a viable alternative to prescribed burning close to population centres and outside the narrow window of suitable weather for prescribed burning. Wide adoption as a management of fire risk will also depend on its effectiveness in the Australian context, financial costs, social acceptance and other impacts on the environment including biodiversity (Ximenes et al. 2017).

3.6 Bushfires (impact risk)

Definition: the risk that forestry activities increase the incidence of bushfires in surrounding areas.

Principal pathway: Forestry activities such as prescribed burning can result in fire escaping into surrounding areas. Bushfires can result in financially significant damage to buildings and other assets, loss of life and damage to high conservation value areas. Prescribed burning can also affect the health of people in surrounding areas through emissions of smoke and particulates (see section 0).

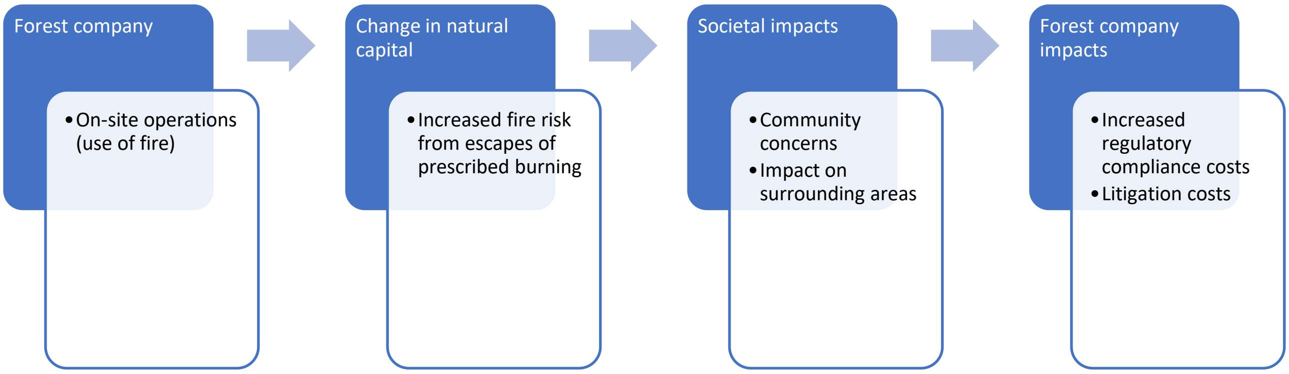

Figure 3-9 Causal pathway describing risks arising from the impact of forestry companies on bushfires

Evidence

Degree of impact (bushfires): Forestry operations such as the use of prescribed burning or the use of forestry machinery can pose a risk to fire escaping to surrounding areas.

The use of fire is now well embedded as part of fire protection systems throughout Australia. Managing the fuel loads in forests through prescribed burning is common for native eucalypt forests and is increasingly also being used to achieve biodiversity outcomes (Burrows and McCaw 2013). Prescribed burning has been reviewed, for example by Fernandes and Botelho (2003) and McCaw (2013), the evidence shows that prescribed burning contributes to safer and more effective fire suppression. Prescribed burning is not used in established plantations, *Pinus radiata* is a fire-sensitive species that can be killed by moderate-intensity fires (Bartlett 2012). However, fire can be used as part of plantation site preparations or to burn slash following harvesting (England et al. 2013). Fire can also be used in native forestry areas of a mixed estate (we consider this risk as part of our native forests sub-category).

Any burning operation runs the risk of escaping control and causing a bushfire. For example, in 2002, 10,000 ha of Wyperfeld National Park in north-western Victoria were damaged when a controlled burn escaped.[11] In Western Australia in 2011/12 an escaped fire at Margaret River caused significant property damage and another, the Milyeannup fire, burned 52,000 ha of forest.[12] The likelihood of the fire escaping and the severity of any fire will depend on fuel properties of the unburnt forest (including its size and age), its proximity to the burn boundary, the weather conditions and any response to suppress the fire.

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[11] https://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/Publications_Archive/CIB/cib0203/03Cib08 (accessed 13 August 2020)

[12] https://www.bnhcrc.com.au/news/2017/great-escapes (accessed 13 August 2020)

The use of forestry machinery can also be a cause of fire ignition (Environment and Natural Resources Committee 2008). Causes can include logging machinery exhausts and chainsaws. For example, a large fire of over 6,000 hectares at Cann River in Victoria was sparked by harvesting equipment in December 2019[13]. While timing of prescribed burns is controlled based on weather and fuel conditions and generally avoided in the summer months, accidental ignition from forest machinery can happen at any point that forestry activities are permissible.

Severity of consequences (bushfires): Where a prescribed burn is planned, the landowner conducting the burn has a duty to ensure the fire is contained, which involves consideration of factors such as the weather, the availability of firefighting resources and the special vulnerabilities of anyone likely to be affected by the fire. Liability has been legally established for fires deliberately lit and then allowed to escape, regardless of whether the fires were lit for cooking, land clearing or hazard reduction (Eburn and Cary 2016). Therefore, landowners and managers face the risk of liability for property damage and death from escaped fires from prescribed burning or land clearing. There is however uncertainty about the extent of liability for private landowners and there have been calls to clarify this, for example, by the Institute of Foresters of Australia:

> *The private landowner's liability for fuel reduction fires is a point of confusion for landowners and is a factor in their involvement in fuel reduction. An understanding is that if a permit is issued, and a burn plan adhered to, the land owner is not liable for fire-fighting costs in the case of an escape. However, there is uncertainty as to whether this extends to civil liabilities for property damage* (IFA 2019 p.10).

Liability for failing to reduce fuel loads, and so possibly contributing to fire spreading from one property to another, is theoretically possible, but would be legally difficult to establish and is not something that has precedent (Eburn and Cary 2016).

Public liability insurance against the financial consequences of escaped burns can potentially mediate the risk for forestry companies. A relevant case study is provided by the class action against the power company AusNet for the 'Black Saturday' fires in Victoria. An AusNet powerline failed and caused a fire which spread to Kilmore East-Kinglake and Murrindindi-Marysville and killed 119 people. AusNet settled in the case for A$300 million and their insurance covered all its liabilities[14]. Although the case is different to an escaped prescribed burn it suggests that public liability insurance may cover forestry companies against claims of damage from injury or damage to a person or property. Due to the potential high value claims against forest owners a higher level of liability insurance may be required that can increase costs.

The ability to undertake prescribed burning, particularly close to urban areas, can also be limited through social concerns expressed by communities, for example, about the health and well-being impacts of smoke, ash, dust and smells, effects on water quality, greenhouse emissions, effects on wildlife, and fear of the fire escaping (Bell and Oliveras 2006, Altangerel and Kull 2013). It is also possible that the timing of forestry harvesting activities may be further restricted in the future from the increase in the length of the fire season and through regulation around activities taking place on moderately high fire risk days.

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[13] https://www.theage.com.au/national/fire-crews-battle-cann-river-blaze-20091219-l686.html (accessed 15 December 2020)

[14] https://insuranceandrisk.com.au/bushfire-liability-claims-soar-to-800m/ (accessed 25 November 2020)

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Bushfire risk (e.g. spread and intensity) can be affected by recent drought-induced die-off due to increased deadwood material and higher near-ground solar radiation (Ruthrof et al. 2016).
Water quality (impact risk) Section 3.3	• Water quality risk can be affected by bushfires, for example, when post fire rainfall washes contaminants into waterways and reservoirs.
Temperature (Dependency risk) Section 3.4	• Temperature risk and fire risk interact. Extreme high temperatures can increase fuel dryness and changing the supply of fine fuel (leaf litter) (Clarke et al. 2016).
Storms and floods (dependency risk) Section 3.7	• Bushfire risk can be affected storm conditions such as wind and lightning and extreme fire events are associated with strong, deep cold fronts.
Soil quality (dependency/impact risk) Section 3.8	• Soil quality risk is affected by fire, as shown by changes to soil nutrients and erosion post fire.
Biodiversity (dependency/impact risk) Section 3.12 and 3.13	• Biodiversity risk and bushfire risk interact. For example, Fires can affect forest biodiversity and forest functioning. In addition, harvest residues provide fuel for bushfires and quick microbial decomposition of that residue can reduce fire risk. Transitions to alternative vegetation states/structures could also result in a positive flammability feedback (Coppoletta et al. 2016, Tepley et al. 2018, Burton et al. 2019).
Weeds (dependency/impact risk) Section 3.14 and 3.15	• Weed risk can interact with bushfire risk. For example, some weeds are particularly flammable. There is a risk that soil disturbance associated bushfire will promote weed establishment.
Pests and diseases (dependency/impact risk) Section 3.16 and 3.17	• Pests and diseases risk interacts with bushfire risk. For example, pests and disease tree mortality can increase the fire risk, and in addition, fire can damage trees and make they more susceptible to pests and diseases.
Greenhouse gases (impact risk) Section 3.19	• Greenhouse gas risk can be affected by fire from the significant greenhouse gas emissions that are associated with fires.
Other air emissions (impact risk) Section 3.20	• Air emission risk can be affected by fire. For example, from the emissions of particulates and other air pollutants in smoke and dust from burnt areas.

MATERIALITY	
SOFTWOOD PLANTATIONS	**MODERATE**
HARDWOOD PLANTATIONS	**MODERATE**
NATIVE FORESTS	**HIGH**

SOFTWOOD PLANTATIONS — **MODERATE**

- **Degree of impact: Moderate –** Machinery-started fires are a moderate risk for plantations due to the year-round operations, including in the summer months. Prescribed burning is not used in established plantations but there may be some use of fire during site preparation or following harvesting to burn slash.
- **Severity of consequences: Moderate** – There is evidence of community concern regarding forestry estates and the perception of increased fire risk, there is also a risk that the timing of forestry activities may be restricted further. The financial consequences for forestry companies from escaped burns are potential very large, however, the management and regulation around lighting fires, the control of fuel, and potential for insurance mitigates the risk.

HARDWOOD PLANTATIONS — **MODERATE**

- **Degree of impact: Moderate –** As for softwood plantations
- **Severity of consequences: Moderate** – As for softwood plantations.

NATIVE FORESTS — **HIGH**

- **Degree of impact: High –** Fire plays an important role in native forest management. It is used to create a favourable seedbed following logging, to achieve biodiversity outcomes and as part of fuel reduction burns. The more frequent and extensive use of fire in native forests means that the risks of escape are higher.
- **Severity of consequences: Moderate** – As for softwood plantations.

Risk mitigation options

- This risk can be mitigated by strategically and actively managing the landscape through prescribed burning programs so as to avoid the development of large areas of unburnt vegetation with high fuel loads and through insurance.
- The risk of a prescribed burn escaping can be mitigated by consideration of factors such as the weather, the availability of firefighting resources and the special vulnerabilities of anyone likely to be affected by the fire. In addition, avoiding burning in a warming, drying weather phase (spring) can also help reduce risk.
- Liability insurance can cover forestry companies and individuals against claims of damage from injury or damage to a person or property. Forestry companies require a high level of cover to mitigate against the potential of large claims.

3.7 Storms and floods (dependency risk)

Definition: the risk of lower productivity, tree mortality, and increased costs due to exposure to storm and flood events. As droughts are covered under water availability (section 3.1), heatwaves under temperature extremes (section 3.4) and bushfires in section 3.5, this section concentrates on other storm events, including floods, wind, cyclones, thunderstorms and hail.

Principal pathway: Storms and flood can cause damage to trees (through windthrow and direct crown or root damage), as well as to access roads, bridges and other assets, resulting in loss of production and/or subsequent clearing, replanting and rebuilding/repair costs. Damaged trees can in turn cause damage to residual trees, increase susceptibility to pests and diseases, create opportunities for weeds, harm biodiversity, increase bushfire fuel load and limit access for both management and recreational activities. Climate change has the potential to increase the frequency, severity and/or duration of storms and floods in future.

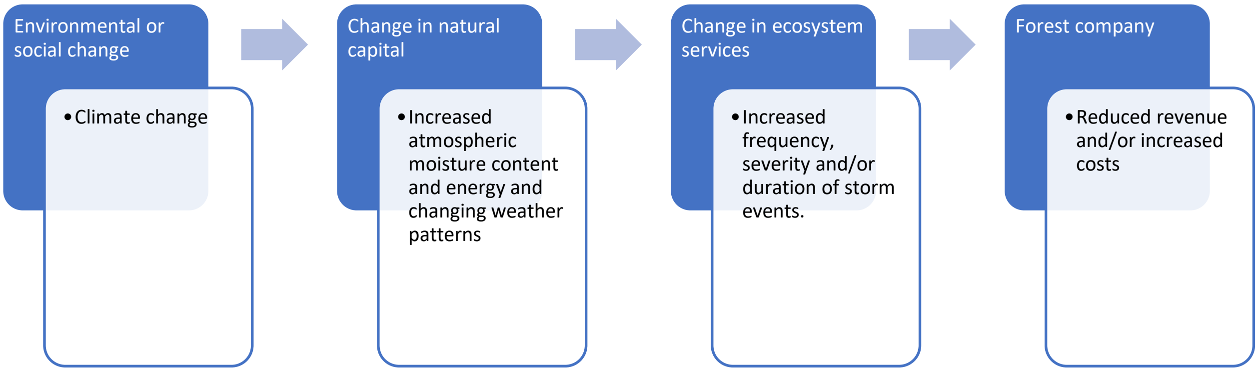

Figure 3-10 Causal pathway describing risks arising from the dependency of forestry companies storm and flood events

Evidence

Degree of dependency (storms and floods): Storm events such as floods, wind storms, cyclones, hail, and lightning are a cause of forest damage and tree mortality.

Wind is a major cause of forest loss around the world – for example, storms were responsible for 53% of damage to European forests from natural disturbances between 1950 and 2000, and single severe storm events in 1990 and 1999 damaged 120 and 180 million cubic metres of wood, respectively (Schelhaas et al. 2003). In tropical regions, cyclones can also be a major cause of forest loss and disturbance. Plantations of trees, especially those with natural ranges outside cyclone-affected zones, are often badly affected by cyclones (Bellingham 2008).

The susceptibility of trees to wind damage is governed not just by the wind climate but also by forest structure, tree characteristics, and landscape characteristics (Cremer 1984a). Wood et al. (2008) observe that wind damage was not a serious concern in Tasmanian native forests previously harvested under a clearfelling regime, but note that wind risk is more significant now that most native forests are harvested under an aggregated variable retention regime. Wind damage increases as retention levels decrease, fetch increases and aggregate size decreases (Wood et al. 2008). Monitoring of a sample of ten Tasmanian aggregated retention native forest coupes in the mid-2000s found less than one windthrown tree per hectare of felled area, suggesting that the economic impact was negligible (Wood et al. 2008). However, the authors note that as regrowth native forests are managed more intensively, the risk of wind damage may increase towards the levels seen in plantations, where financial losses associated with windthrow after thinning operations can be considerable (Wood et al. 2008). In plantations, the key risk period is immediately following thinning, particularly where tree height:diameter ratios exceed 20:1 (Neilson 1990).

Some plantations experience waterlogging associated with inundation events. Waterlogging reduces stem and root growth in native and non-native plantations, and can cause mortality in some situations (Hollingsworth et al. 1996, Marcar et al. 2002). Mummery and Battaglia (2004) estimated that waterlogging reduced stand growth of eucalypt plantations by between 30% and 50%.

Thunderstorms in Australia can cause lightning and large hailstones. Lightning is a direct cause of tree damage around the world and can be an important cause of mortality in certain forests. Despite this the frequency and distribution of lightning-caused tree mortality in uncertain for most forests with a lack of quantifiable evidence (Yanoviak et al. 2017). Hail can also cause damage to trees with plantations in Australia likely to experience about two damaging hailstorms per 35-year rotation (Cremer 1984a). Hailstones can damage bark and cause defoliation through knocking needles and thin shoots off the trees and cause the trees to be more susceptible to shoot dieback associated with infection by Diplodia pinea (Cremer 1984b).

Severity of threat (storms and floods): The effect of climate change on future wind speeds is currently uncertain (Torralba et al. 2017). Historical average wind speeds have shown evidence of a reduction over land since the 1980s (a process known as stilling (McVicar et al. 2008, McVicar et al. 2012)), however, recent evidence shows this trend has reversed (Zeng et al. 2019). It is probably more important to consider severe storms with extreme wind speed as it is these storm events that tend to cause significant damage to standing trees. Walsh et al. (2016) show that the risks are likely to vary regionally, and also vary by storm type, for example, they investigate hailstorms, tropical cyclones, extra-tropical cyclones, east-coast lows, and severe thunderstorms. The level of certainty regarding future predictions for each of these storm types is low and further research is needed (Walsh et al. 2016). However, if the frequency or severity of storms were to increase, then it is likely to lead to increased risk of windthrow and stem breakage in forestry. A small number of studies around the world have modelled the effects of climate change and the probability of wind damage. For example, increased productivity under climate change in Swedish forests will likely lead to increased wind damage (Blennow et al. 2010a, Blennow et al. 2010b) as vulnerability increases with tree height:diameter ratios (Reyer et al. 2017). Moore and Watt (2015) found similar results for their models of wind effects under climate change in New Zealand. They showed that increased tree height under the different emissions scenarios had the greatest impact on the risk of wind damage. The risk of wind damage was further increased by modest increases in the extreme winds predicted to occur.

There is evidence from observed weather station records that a higher proportion of total annual rainfall in recent decades has come from heavy rain days (CSIRO and Bureau of Meteorology 2018). As the climate warms, heavy rainfall is expected to become more intense, based on the physical relationship between temperature and the water-holding capacity of the atmosphere. For heavy rain days, total rainfall is expected to increase by around 7 per cent per degree of warming. For short-duration, hourly, extreme rainfall events, observations in Australia generally show a larger than 7 per cent increase. Short-duration rain extremes are often associated with flash flooding. An increase in the intensity of extreme rainfall is projected for most regions.

In Australia, the trend in thunderstorm frequency is uncertain. Historical records are spatially and temporally incomplete and climate models are limited in their capacity to simulate thunderstorm environments (Allen and Karoly 2014, Allen and Allen 2016, Spassiani 2020). For cyclones, (Knutson et al. 2010) show that globally the severity of cyclones is projected to increase as a result of climate change over the next century, however, the frequency of cyclones is projected to decrease.

LINKS TO OTHER RISKS	EXPLANATION
Water quality (dependency risk) Section 3.3	• Water quality risks from forestry activities can be exacerbated by storms, with the magnitude of impacts dependent on factors such as road construction techniques, soil texture and slope (Boston 2016).
Bushfire (dependency/impact risk) Section 3.5 and 3.6	• Bushfire risk can be affected storm conditions such as wind and lightning and extreme fire events are associated with strong, deep cold fronts.
Soil quality (dependency/impact risk) Section 3.8 and 3.9	• Soil quality risk can be affected by storms, for example, through erosion.
Biodiversity (dependency/impact risk) Section 3.12 and 3.13	• Biodiversity risk can be affected by storms through changes to species populations or forest functioning.
Pests and diseases (dependency/impact risk) Section 3.16 and 3.17	• Pests and disease risk and storm event risk interacts. For example, storm events can damage trees and make them more susceptible to pests and disease, in addition, trees already suffering from pests and disease damage may be more susceptible to storm damage.

MATERIALITY

SOFTWOOD PLANTATIONS — **HIGH**

- **Degree of dependency**: **High.** Storm and flood events can substantially reduce productivity and tree survival.
- **Severity of threats**: **High.** Due to the possible increase in vulnerability due to increased tree height:diameter ratios under climate change, combined with uncertainty around future frequency, severity and duration of storm events.

HARDWOOD PLANTATIONS — **HIGH**

- As for softwood plantations

NATIVE FORESTS — **HIGH**

- **Degree of dependency**: **Low** under clearfelling regimes. **Moderate** under variable retention regimes.
- **Severity of threat**: **High.** As for softwood plantations.

Risk mitigation options

A range of risk mitigation options are available and already widely practiced in Australian forestry, including:

- *Site selection*: avoiding the establishment of plantations in areas with high flood or windthrow risk, such as floodplains, sites with shallow or waterlogged soils, elevated or exposed terrain and cyclone-prone areas in northern Australia (Wood et al. 2008, Pinkard et al. 2015).
- *Management*: Managing plantations to achieve a maximum height:diameter ratio of 20:1 is recommended on wind-prone sites, through modifying initial spacing or thinning before the height:diameter ratio exceeds the threshold. Fertiliser application can be delayed on exposed sites to encourage deeper root growth, and likewise post-thinning applications can be delayed or avoided if there is a risk of increasing crown 'sail area' (Wood et al. 2008). The timing and intensity of thinning operations can be optimised to minimise windthrow risk and avoid higher-risk situations such as thinning in stands with a mean dominant height >20m (Wood et al. 2008). Insurance against wind losses is also available in Australia.[15]

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[15] https://www.forestry.org.au/Forestry/Membership/Insurance/Plantation insurance/Forestry/Membership/Insurances/Insurance.aspx?hkey=f5fa4bae-a055-492c-858c-6387ecc5dc1c (

3.8 Soil quality (dependency risk)

Definition: the risk of lower productivity and increased costs due to poor soil quality (Ascui and Cojoianu 2019a).

Principal pathway: Forestry companies are highly dependent on soil quality in order to produce wood products, as trees depend on soil for nutrients, moisture retention and structural support. Soil quality influences growth rates, survival and wood properties. Hence economic returns are closely linked to soil quality. The quality of soil may be negatively affected by a variety of processes, including forestry operations (see section 3.9), and external processes such as bushfires, drought or floods (see section 3.7).

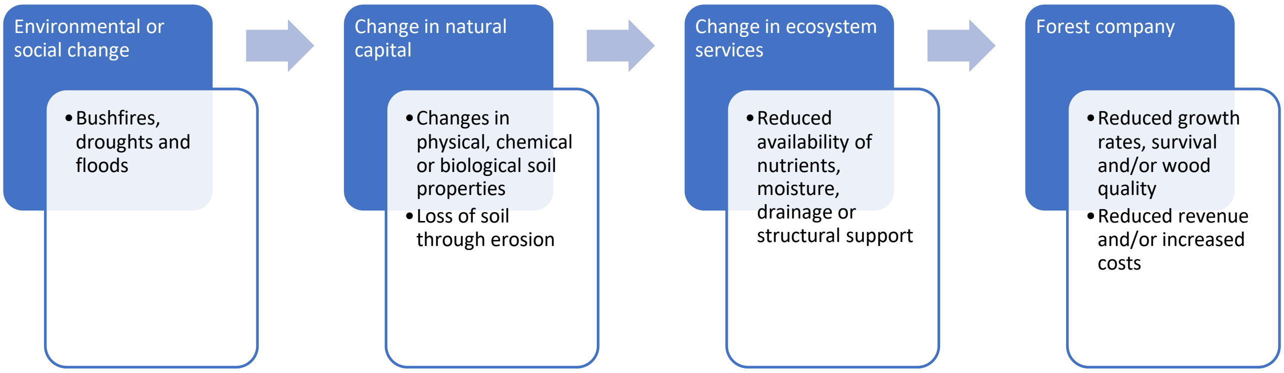

Figure 3-11 Causal pathway describing risks arising from the dependency of forestry companies on soil quality

Evidence

Degree of dependency (soil quality): Soil underpins forest productivity. It is involved in the supply of water and nutrients required for forest growth. Plantations require soils with moderate to good fertility, good drainage to 800 mm depth, and a minimum of 800 mm of soil depth available for root growth (Neilson 1990). Watt et al. (2008) show radiata pine achieves optimum growth (mean annual increment) at soil porosities of 63–64% porosity. In order to be economically viable in Australia, sites need to be capable of producing a mean annual increment of at least 15 m^3 ha^{-1} without fertilising (Neilson 1990).

Nutrient concentration in the soil affects tree growth. Site studies have shown that the most important nutrients controlling radiata pine growth are the concentrations of phosphorus and nitrogen (or, alternatively, the C:N ratio) (Watt et al. 2008, Mead 2013). The relationship shows growth increasing from levels of nutrient deficiency through to levels of adequacy and then growth decreases as nutrient concentration reaches levels of toxicity (Mead 2013). For *Pinus radiata* the values for a whole range of nutrients which separate deficiency from adequacy are outlined in (Mead 2013). For example, for nitrogen it is 1.2-1.4% foliage concentration and for phosphorus it is 0.11-0.14% foliage concentration.

PH level has been shown to be generally less important to *Pinus radiata* growth than nutrients (Romanyà and Vallejo 2004). Some research suggests that the optimum pH range for radiata pine is 4.1–5.7, however, it will tolerate a pH range from 3.6 to 7.1 (Romanyà and Vallejo 2004, Mead 2013).

Severity of threat (soil quality): Threats to soil quality include climate change and forestry operations.

Soil quality changes are determined by very complex interactions between climate, terrain, vegetation and soil type. Changes are likely to be location specific and occur over different timescales, ranging from a few days following severe disturbances to many decades if there is a change in vegetation structure. Soil quality changes can also either be magnified or mitigated by management activities. Forest management practices can affect soil compaction, nutrient removal and erosion rates, with consequent impacts on production.

Soil quality in forested areas is directly affected by climate and weather, including temperature, CO_2 concentration, precipitation frequency and intensity, and events such as heat waves, droughts and storms. Soil quality can also be indirectly affected by other events including pest and disease outbreaks, fire, vegetation growth and species composition (Raison and Khanna 2011). For example, litter fall is an important pathway for nutrient return to the soil and changing vegetation growth can affect the type and volume of litter fall, while climatic conditions can change the decomposition rate (Krishna and Mohan 2017). Evidence also shows that severe fires can cause an increase in runoff and erosion in eucalyptus forests by enhancing soil hydrophobicity, and increasing sediment transport, mainly through reduced ground cover (Prosser and Williams 1998).

Forests soils include relatively large amounts of carbon stored in forest soil organic matter. The interaction between soil organic carbon and climate change has long been an area of debate (Kirschbaum 2000, Kirschbaum 2006, Lehmann and Kleber 2015). Nevertheless, the climate is considered to have a large effect on soil organic carbon and has been shown to have reasonable explanatory power at global (Carvalhais et al. 2014) and regional scales, including in Australia (Hobley et al. 2015). As temperature increases, soil microbial activity increases, increasing the rate of decomposition of soil organic matter (Davidson and Janssens 2006, von Lützow and Kögel-Knabner 2009). It is generally accepted that rising temperature will result in a loss of stored carbon via this mechanism (Kirschbaum 2000, Medlyn et al. 2011). However, increased temperatures can also accelerate mineralization and stimulate plant and tree growth (Simioni et al. 2008). In some circumstances, enhanced growth can outweigh the loss of soil carbon from decomposition (Medlyn et al. 2011).

Forestry activities are also a threat to future soil quality. Section 3.9 has further details on the threat to tree productivity that come from forestry activities including disturbance, compaction, soil erosion and the management of post-harvest residues.

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Water availability risk can be affected by the ability of soil to hold moisture; forestry activities can impact on soil structure (e.g. causing compaction). • Soil quality risk can be affected by water availability and drought effects.
Water quality (impact risk) Section 3.3	• Water quality risks can be affected by soil erosion and soil degradation (Lane and Sheridan 2002, Aust and Blinn 2004). Major soil disturbance activities such as the establishment of roads and operational infrastructure can cause localised changes in overland flow resulting in erosion (Grigal, 2000), with associated risks of sedimentation to waterways.

Temperature (dependency risk) **Section 3.4**	• Soil quality risk can be affected by changing temperatures, for example, potentially increasing the loss of soil organic carbon (Davidson and Janssens 2006).
Bushfires (Dependency/impact risk) **Section 3.5 and 3.6**	• Soil quality risk is affected by fire, as shown by changes to soil nutrients and erosion post fire.
Storms and floods (dependency risk) **Section 3.7**	• Soil quality risk can be affected by storms, for example, through erosion.
Fertiliser (dependency risk) **Section 3.10**	• Soil quality and fertiliser risk are linked since the requirement for fertiliser is dependent upon soil nutrients.
Contamination and waste (impact risk) **Section 3.11**	• Soil quality can be affected by chemical contamination which may affect soil physical, chemical and biological properties (Abosede 2013, Klamerus-Iwan et al. 2015).
Biodiversity (dependency/impact risk) **Section 3.12 and 3.13**	• Soil quality risk is linked to soil biodiversity and vegetation biodiversity. For example, forestry activities e.g. harvesting and chemical use can affect soil condition and soil biodiversity (Yasmin and D'Souza 2010). Changes in soil biota associated with forestry operations can affect nutrient and carbon cycling in forest soils and physical characteristics such as density, thereby affecting soil quality.
Weeds (dependency/impact risk) **Section 3.14 and 3.15**	• Weed risk can be affected by soil quality and soil disturbance associated with forestry operations.
Greenhouse gases (impact risk) **Section 3.19**	• Greenhouse gas risk can be affected by forestry activities which impact stored soil carbon and prevent the soil reaching its potential for carbon sequestration.

MATERIALITY

SOFTWOOD PLANTATIONS

HIGH

- **Degree of dependency**: **High.** Forest productivity is strongly dependent on soil quality. While there is evidence that softwood plantations are viable in a wider range of soil conditions than hardwood plantations the degree of dependency is still high.
- **Severity of threat: Moderate.** Threats to soil quality include forestry operations and climate change. Forestry operations can increase compaction and change nutrient availability reducing tree growth in following rotations (see section 3.9). Changes due to climate change are likely to be location specific and occur over different timescales.

HARDWOOD PLANTATIONS

HIGH

- **Degree of dependency**: **High.** As for softwood plantations.
- **Severity of threat: Moderate.** As for softwood plantations.

NATIVE FORESTS

HIGH

- **Degree of dependency**: **High.** As for softwood plantations.
- **Severity of threat: Moderate.** As for softwood plantations.

Risk mitigation options

Soil properties and characteristics are a critical consideration in planting regimes and decisions on whether and how to improve the site to increase productivity. Below are some of the key mitigation options:

- *Matching appropriate tree species to the site*: different species can tolerate different soil properties and the choice of species may mitigate affects such as tree stress, tree mortality and loss of productivity.
- *Manage soil nutrients*: Nutrient deficiencies can be corrected by applications of fertilisers**.** Nitrogen deficiency can be corrected by using nitrogen rich fertiliser or by using nitrogen-fixing legumes. Phosphorus deficiency is commonly corrected using the application of calcium phosphate fertilisers such as superphosphate. Other nutrient deficiencies which can occur and be corrected by fertiliser applications include boron deficiency (where calcium borate fertilisers are used) and potassium deficiency (where potash fertilisers are used).
- *Selection of sites with good quality soils*: forestry companies can also choose sites that have soil quality that enables strong tree growth and productivity.

3.9 Soil quality (impact risk)

Definition: the risk that forestry activities negatively affect soil quality.

Principal pathway: Forestry operations can have negative impacts on soil quality through physical disruption or compaction, erosion, chemical use and accidental spills (considered in section 3.11). These impacts can directly affect forest productivity as well as result in adverse effects on other ecosystems, for example through sedimentation or chemical contamination of waterways (considered in section 3.3), or contributing to climate change through loss of soil organic carbon (see section 3.19).

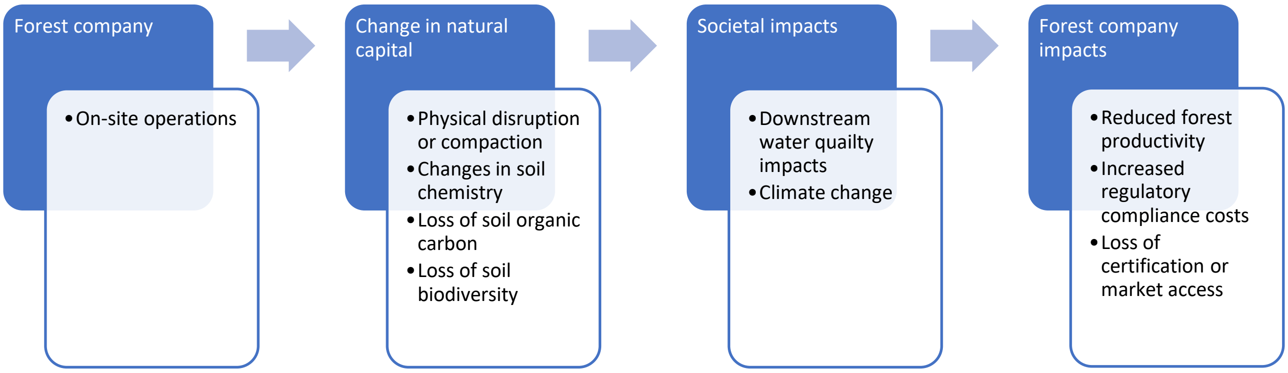

Figure 3-12 Causal pathway describing risks arising from the impact of forestry companies on soil quality

Evidence

Degree of impact (soil quality): Soil is highly sensitive to disturbance (Cambi et al. 2015). Major activities associated with the physical disruption of forest soil include establishment of road networks and operational infrastructure, and compaction related to the use of heavy machinery. These can additionally cause effects such as localised changes in overland flow resulting in ponding, waterlogging and erosion (Grigal 2000). Management activities also can affect soil carbon, nitrogen and carbon to nitrogen (C:N) ratios (Jandl et al. 2007). Chemicals used to control weeds and pests can accumulate in the soil, influencing soil biota such as earthworm populations (Yasmin and D'Souza 2010). In general, these activities are undertaken during specific windows of time that relate to site preparation and early establishment, thinning (if undertaken) and harvesting.

Forestry operations can increase soil erosion by loosening the soil and by removing groundcover, which exposes the soil. Forest operations in certain locations and at certain times have a higher hazard of soil erosion, for example, harvesting on slopes and using forestry machinery whilst the soil in saturated. In addition, forestry machinery and associated infrastructure can cause soil compaction and water channelling, the compacted soil is more likely to suffer from rainfall runoff (which takes soil particles with it) and water channels can concentrate the rainfall which can increase the amount of dislodged soil (Elliot et al. 1998).

The way that site residues are managed post-harvest or pre-establishment can have significant impacts on soil quality. Management practices that accelerate loss of soil organic matter and nutrient reserves are a major cause of declines in site productivity both within and between rotations (Smethurst and Nambiar 1990b, O’Hehir and Nambiar 2010). In plantation forests, fire has historically been used to manage forest residues, although this is now a less common practice, reflecting greater understanding of the role of fire in depleting soil nutrients and organic carbon. More commonly, residues are maintained on site and incorporated back into the soil using chopper rollers. However, fire still plays an important role in native forest management. It is used to create a favourable seedbed following logging, mimicking natural regenerative processes in these forests (Battaglia 1993).

The effect of harvesting on soil organic carbon (SOC) has been studied in *Eucalyptus regnans* forest in Victoria. The study showed either a decrease in SOC associated with mechanical disturbance of the soil or no change in the first 10 years following harvesting. Where slash was burnt post-harvest, there was no significant change in SOC 10 years after harvesting. For long-term (multi-decadal) trends the change was related to the intensity of the harvest system, with the direction of the effect differing for clearfell and slash burn systems, all of which reported a decrease in SOC, versus selection systems, which reported an increase. International meta-analyses have shown that: i) there are small decreases in SOC when using harvest systems that remove large amounts of biomass (such as whole tree harvesting), or on particular soil types (or site preparations); and ii) there are small increases in SOC immediately following harvest where large amounts of residues are produced, and incorporated into the soil (England et al. 2014).

Severity of consequences (soil quality): The consequences of soil quality degradation can be directly felt by forestry companies through impacts on tree growth and productivity, or through indirect impacts such as regulation or social concern.

Soil erosion and soil compaction from forestry operations can have consequences for productivity for forestry companies. Reductions in productivity between rotations can be significant (Kozlowski 1999, Tan et al. 2005). For example, compaction typically alters soil structure and hydrology by increasing soil bulk density, soil strength and water runoff and at the same time decreasing soil porosity, aeration and infiltration capacity (Kozlowski 1999). Compactness has been shown to decrease Radiata pine rooting density when soil strength is above 3,000 kilopascals (Mead 2013). This critical value is often used to determine whether to improve the site to ensure good tree growth in the next rotation.

In Australia, social concern and regulation consequences are mitigated by well-developed forest practices guidance and mitigation options. The impacts of forestry practices on soil quality are regulated by state governments. For example, in Tasmania, forest managers are required to prepare Forest Practices Plans (FPPs) in accordance with the Tasmanian Forest Practices Code 2015 (Forest Practices Authority 2015), which includes practices to prevent unacceptable rates of erosion and landslides, nutrient loss, compaction, puddling and mixing of soils, during and after forest operations. In addition, voluntary certification standards such as the FSC National Forest Stewardship Standard of Australia (FSC Australia 2018) require forest managers to identify and implement effective actions to prevent negative impacts on environmental values (including soils), and to mitigate and repair those impacts that do occur, proportionate to their scale, intensity and risk. Where forest owners are seeking FSC endorsement of promotional claims related to the provision of soil conservation as an ecosystem service, they must ensure that vulnerable or high-risk soils are identified and actions are taken to reduce compaction, erosion and landslides, and maintain, enhance or restore soil stability and fertility (FSC Australia 2018). It is possible that more restrictive or costly practices could be imposed by regulation or voluntary certification schemes in future.

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Water availability risk can be affected by the ability of soil to hold moisture; forestry activities can impact on soil structure (e.g. causing compaction). • Soil quality risk can be affected by water availability and drought effects.
Water quality (impact risk) Section 3.3	• Water quality risks can be affected by soil erosion and soil degradation (Lane and Sheridan 2002, Aust and Blinn 2004). Major soil disturbance activities such as the establishment of roads and operational infrastructure can cause localised changes in overland flow resulting in erosion (Grigal, 2000), with associated risks of sedimentation to waterways.
Temperature (dependency risk) Section 3.4	• Soil quality risk can be affected by changing temperatures, for example, potentially increasing the loss of soil organic carbon (Davidson and Janssens 2006).
Bushfires (Dependency/impact risk) Section 3.5 and 3.6	• Soil quality risk is affected by fire, as shown by changes to soil nutrients and erosion post fire.
Storms and floods (dependency risk) Section 3.7	• Soil quality risk can be affected by storms, for example, through erosion.
Fertiliser (dependency risk) Section 3.10	• Soil quality and fertiliser risk are linked since the requirement for fertiliser is dependent upon soil nutrients.
Contamination and waste (impact risk) Section 3.11	• Soil quality can be affected by chemical contamination which may affect soil physical, chemical and biological properties (Abosede 2013, Klamerus-Iwan et al. 2015).
Biodiversity (dependency risk) Section 3.12	• Soil quality risk is linked to soil biodiversity and vegetation biodiversity. For example, forestry activities e.g. harvesting and chemical use can affect soil condition and soil biodiversity (Yasmin and D'Souza 2010). Changes in soil biota associated with forestry operations can affect nutrient and carbon cycling in forest soils and physical characteristics such as density, thereby affecting soil quality.
Weeds (dependency/impact risk) Section 3.14 and 3.15	• Weed risk can be affected by soil quality and soil disturbance associated with forestry operations.

Greenhouse gases (impact risk) **Section 3.19**	• Greenhouse gas risk can be affected by forestry activities which impact stored soil carbon and prevent the soil reaching its potential for carbon sequestration.

MATERIALITY

SOFTWOOD PLANTATIONS	**HIGH**

- **Degree of impact: High.** Forestry operations have the potential to have significant impacts on soil erosion, compaction, and organic matter between rotations with potentially significant reductions in productivity.
- **Severity of consequences**: **Moderate.** The reduction in productivity will affect forestry revenue. The risk is mitigated by the fact that site management practices to minimise impacts are well known and many embedded in existing regulations and certification frameworks.

HARDWOOD PLANTATIONS	**HIGH**

- **Degree of impact: High.** As for softwood plantations
- **Severity of consequences**: **Moderate.** As for softwood plantations

NATIVE FORESTS	**HIGH**

- **Degree of impact: High.** As for softwood plantations
- **Severity of consequences**: **Moderate.** As for softwood plantations

Risk mitigation options

Site management practices for minimising impacts on soil quality are well known, and some are embedded into Forest Practices Codes. The move away from burning forest residue has reduced risks to soil quality from plantation management practices. Other mitigation options include:

- *Integrated approach* to site infrastructure planning that accounts for soil and topographical characteristics.
- *Precision site preparation* on erosion-prone sites or those with soils susceptible to physical damage. This can include preparation of individual planting holes rather than broadscale site preparation (Neilson 1990).
- *Manage soil compaction and erosion*: Soil compaction and loss of soil through erosion can be managed through careful planning of operations and compliance with codes of practice designed to minimise impacts on soil and other values (Forest Practices Authority 2015). This includes the systematic assessment of soil erosion and compaction hazard and the implementation of site-specific measures to protect soil including managing the timing and location of harvesting activities. Apply mechanical residue management techniques in plantations.
- *Manage soil nutrients*: Issues such as nutrient depletion through residue management practices can be overcome by using alternative approaches, such as changing residue management away from burning to reduce nutrient and soil organic carbon depletion.

3.10 Fertiliser use (dependency risk)

Definition: the risk that non-renewable inputs to fertiliser may be priced at higher levels in future. The impact risks of fertiliser application causing water pollution and greenhouse gas emissions are treated in sections 3.3 and 3.19, respectively.

Principal pathway: Fertiliser is an important input applied to forests. Commonly for plantations, individual fertiliser is applied during planting or very shortly after and then again during mid-rotation and is a major component in enhancing the productivity and profitability of the company. The availability and cost of fertiliser is therefore a component of financial performance for forestry companies.

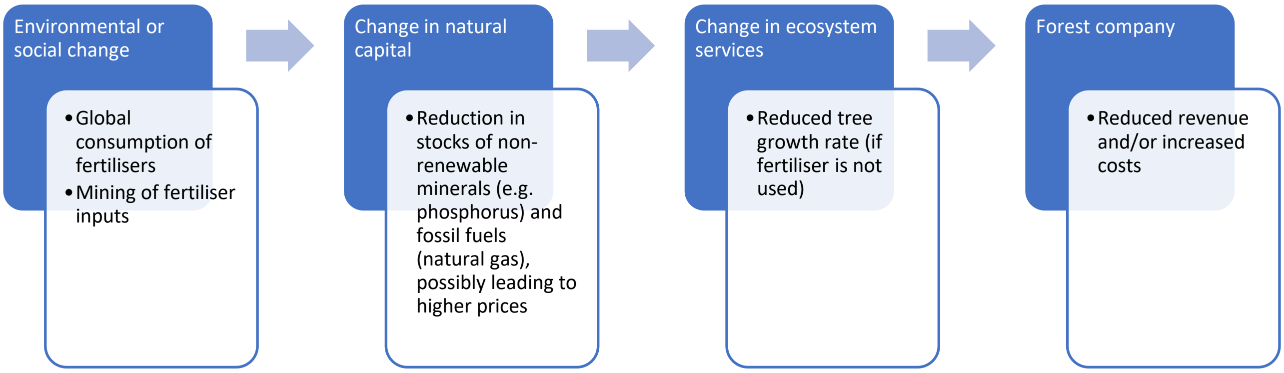

Figure 3-13 Causal pathway describing risks arising from the dependency of forestry companies on fertiliser

Evidence

Degree of dependency (fertiliser): The amount and type of fertiliser used in forestry depends on biophysical factors (nutritional deficiencies in the soil), and economic factors (balancing wood production and the cost of fertiliser to maximise profit). Fertiliser use is common in hardwood plantations but less so in softwood plantations in Australia and not commonly used in managed native forests (May et al. 2009). The amount of fertiliser applied at different stages of the rotation varies with species and with the intended wood products. Fertilisation is a costly process for forestry companies, and applications are therefore kept to a minimum, whilst balancing the nutrient requirements for productive growth. The overall application rate per hectare of fertiliser is low, in total forestry fertiliser use is approximately 1% of the total used across Australia each year (May et al. 2009).

An economic analysis in May et al. (2009) showed that the profitability of fertiliser applications in both hardwood and softwood plantations tended to be greatest at mid and late rotation. Fertiliser at establishment was not profitable for either hardwood or softwood. Fertilising hardwood plantations resulted in Net Present Values (NPV's) of >$400 per hectare for young plantations (2 years) and >$1200 per hectare for mid-rotation plantations (7 years). Fertilising softwood plantations resulted in NPV's of $8 for young plantations (5 years) $568 for mid-rotation (15 years) and $513 for late rotation (25 years). The greater profitability from fertilising older plantations was due to faster growth rates and relative responses, and a shorter time to harvest when profits are realised.

While fertiliser increases the volume of wood produced there are concerns that the faster tree growth rate can reduce wood quality (Raymond and Muneri 2000, Downes et al. 2014). In particular, density is usually reduced for a period after nitrogen application as a result of reduced fibre wall thickness. However, on average, the increased volume of wood produced tends to outweigh any reduction in wood quality and so the overall value of logs produced is generally increased by fertiliser applications (May et al. 2009).

Severity of threat (fertiliser): Changes to fertiliser price could have ramifications for plantation forest growers. The most common forms of fertiliser used in Australian forestry are NPKS blends, urea, sulphur-coated urea and DAP (diammonium phosphate). Prices of fertiliser in Australia have fluctuated but over the last 20 years the trend is a relatively modest increase.[16] However, one important exception to this is the price shock of 2008 where fertiliser prices increased dramatically, with prices of urea and DAP tripling, before prices then fell back rapidly at the end of 2008. Plantation forestry is vulnerable to such price shocks as fertiliser is an important input. However, the timing of some mid-rotation applications may be flexible, allowing more resilience to price shocks compared to other industries such as agriculture. Gradual increases in fertiliser prices can also pose risks to plantation forestry. One potential trigger for price increases in future could be increased consideration of non-renewable resource use and pricing of emissions associated with the production of fertilisers and N_2O emissions from soils.

LINKS TO OTHER RISKS	EXPLANATION
Water quality (impact risk) Section 3.3	• Water quality risk can be affected through potential runoff of fertilisers into waterways after application.
Soil quality (dependency and impact risk) Sections 3.8 and 3.9	• Soil quality and fertiliser risk are linked since the requirement for fertiliser is dependent upon soil nutrients.
Weeds (dependency/impact risk) Section 3.14 and 3.15	• Weed risk can be affected by fertiliser applications as it can alter their ability to compete with trees for nutrients, water and light.
Greenhouse gases (impact risk) Section 3.19	• Greenhouse gas risk can be associated with fertiliser use and its contribution to greenhouse gas emissions through the production, transportation and application of fertilisers.

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[16] https://www.indexmundi.com/commodities/?commodity=dap-fertilizer&months=240&currency=aud accessed 18 March 2020

MATERIALITY	
SOFTWOOD PLANTATIONS	**LOW**
• **Degree of dependency: Moderate.** Fertiliser is an important input for some softwood plantations and can increase profits when applied at mid and late rotation. • **Severity of threat**: **Low.** Fertiliser costs are only a small percentage of total forestry costs, meaning business risks are low. The costs can be absorbed to some degree through higher market prices for the timber produced in these plantations.	
HARDWOOD PLANTATIONS	**MODERATE**
• **Degree of dependency: High.** Fertiliser is an important input for hardwood plantations and can increase profits substantially. • **Severity of threat: Low.** The price of fertiliser may be more relevant to economic margins in pulpwood plantations. The impact will be less significant in plantations grown for higher value products.	
NATIVE FORESTS	**N/A**
• Managed native forests are generally not fertilised.	

Risk mitigation options

These are limited and include:

- Precision application of fertiliser, changes in the timing of applications or potentially reducing the numbers of applications.
- Weed control can also reduce competition for the trees and may therefore reduce the quantities of fertiliser required.

3.11 Contamination and waste (impact risk)

Definition: the risk that land is contaminated with various forms of waste, which in turn may impact on natural capital resources such as water, soil and biodiversity, and have significant impacts on human and animal health. The risk associated with soil contaminants leaching to waterways is addressed in section 3.3.

Principal pathway: Forestry companies use a range of chemicals, including pesticides, herbicides, fertilisers, lubricants and other petroleum-based products as part of normal practice. This use raises the potential for accidental spills or deliberate disposal that could result in contamination.

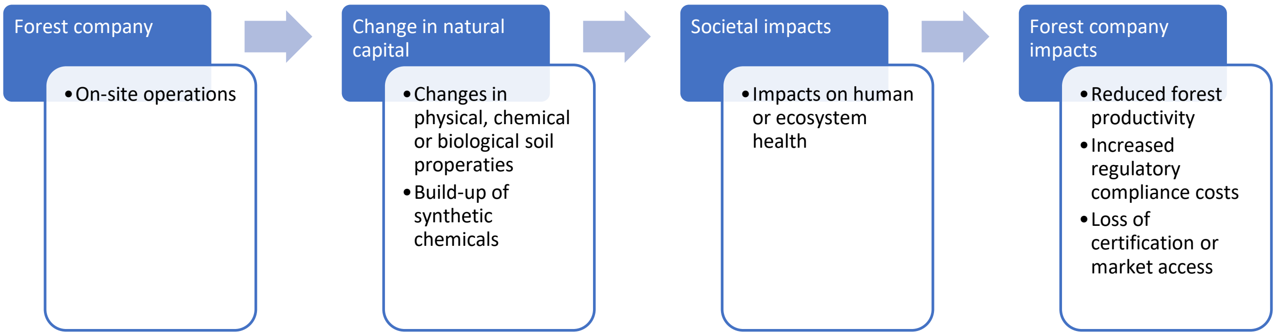

Figure 3-14 Causal pathway describing risks arising from the impact of forestry companies on contamination and waste

Evidence

Degree of impact (contamination and waste): Chemical contamination may affect soil physical, chemical and biological properties (Abosede 2013, Klamerus-Iwan et al. 2015). For example, Klamerus-Iwan et al. (2015) found that leakage of oils used in chainsaws could alter soil physical properties by decreasing the air-filled porosity and increasing water repellence of the soil. Cecutti and Agius (2008) found that three bio-lubricants commonly used in forestry applications posed little risk to the environment, but a commonly used mineral lubricant had significantly lower biodegradability and higher toxicity. Overall, however, there is little evidence of substantial impacts associated with chemical contamination for Australian forestry.

Severity of consequences (contamination and waste): Forestry companies buy, sell, and manage a diversity of sites. They have a legal obligation to manage contamination that is either pre-existing or caused through their activities. There are statutory frameworks and guidelines that identify these obligations (e.g. State Environmental Protection Authority guidelines; State and Federal legislation). In addition, voluntary certification standards such as the FSC National Forest Stewardship Standard of Australia (FSC Australia 2018) require forest managers to ensure that waste materials are disposed of in an environmentally appropriate manner. Where forest owners are seeking FSC endorsement of promotional claims related to the provision of soil conservation as an ecosystem service, they must further ensure that they can demonstrate that chemicals and waste are not discharged to soil (FSC Australia 2018). It is possible that more restrictive or costly practices could be imposed by regulation or voluntary certification schemes in future. However, the materiality of this risk is considered to be low, due to the availability of well-understood mitigation options.

LINKS TO OTHER RISKS	EXPLANATION
Water quality (impact risk) Section 3.3	• Water quality risks can be affected by soil erosion and soil degradation (Lane and Sheridan 2002, Aust and Blinn 2004).
Soil quality (dependency/impact risk) Section 3.8 and 3.9	• Soil quality can be affected by chemical contamination which may affect soil physical, chemical and biological properties (Abosede 2013, Klamerus-Iwan et al. 2015).

MATERIALITY	
SOFTWOOD PLANTATIONS	LOW
• **Degree of impact: Low.** There is little evidence of significant land contamination resulting from Australian forestry. • **Severity of consequences**: **Low.** Impacts are already well managed and mitigation options are well understood.	
HARDWOOD PLANTATIONS	LOW
• As for softwood plantations.	
NATIVE FORESTS	LOW
• As for softwood plantations.	

Risk mitigation options

The mitigation options are well known and covered in regulations related to spill clean-up and reporting procedures.

3.12 Biodiversity (dependency risk)

Definition: the risk of lower productivity and increased costs due to loss of ecosystem services provided by biodiversity. Note that ecosystem disservices provided by biodiversity are considered separately under weeds (section 3.14) and pests and diseases (section 3.16).

Principal pathway: Forestry businesses depend on certain ecosystem services provided by biodiversity, such as pollination services to generate seed for future crops. These services can be threatened by landscape-level and/or global changes, such as climate change, which can lead to local reductions in abundance or even species extinctions, thus reducing provision of those ecosystem services.

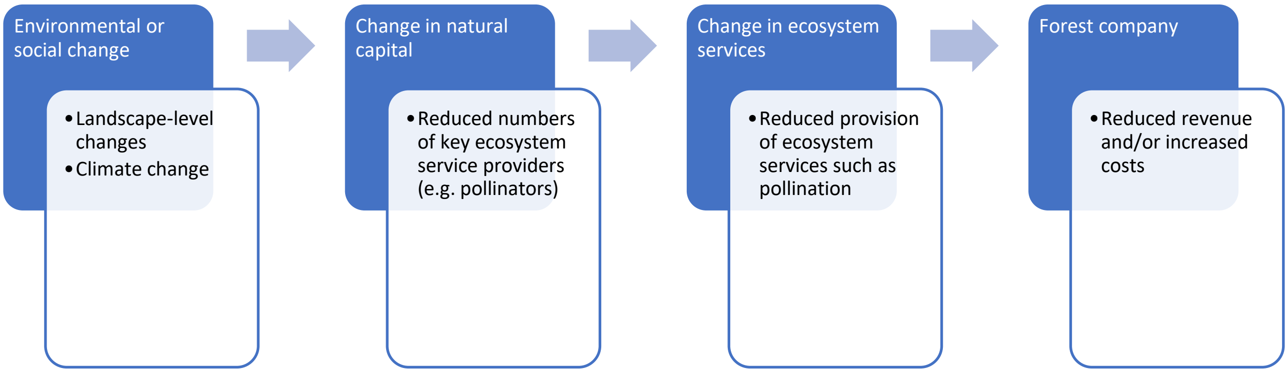

Figure 3-15 Causal pathway describing risks arising from the dependency of forestry companies on biodiversity

Evidence

Degree of dependency (biodiversity): Biodiversity can contribute to forestry productivity in a number of ways. Pollinators fertilise trees resulting in the formation of seeds, soil biota contribute to nutrient cycling, mycorrhizae (symbiotic fungus-root associations) can assist in nutrient and water uptake, and populations of certain species can act as natural enemies of key pests.

Seed stocks for production forestry in Australia are derived from seed orchards (eucalypt plantations) or collection of wild seed (native forests). Seed orchards can be open or closed pollinated, where open-pollinated orchards are reliant on native pollinators to provide the pollination service. Improved seed is commonly sourced from open-pollinated or grafted seed orchards, although broadscale controlled pollination is used for *E. globulus* (Potts et al. 2008). This is not relevant to softwood plantations, as seed generation uses closed-pollination practices and mass seedling generation using micro-propagation and clonal methods is universal in Australia (Wu et al. 2007, Singh et al. 2013).

Logging, both from thinning and final harvest, generates appreciable quantities of residue (Smethurst and Nambiar 1990a, O'Connell 1997, Shammas et al. 2003), and microbial decomposition of this slash provides benefits. The decomposition of the slash supplies nearly all of the early growth demand of replanted *E. globulus* plantations for nitrogen and potassium (Shammas et al. 2003). The microbial biomass that is built from the decomposition of the logging slash also decreases site loss of nitrogen from leaching (Carlyle et al. 1998). A recent review quantified the consequences of removing harvesting residues on subsequent productivity; (Achat et al. 2015) showed tree growth was reduced by 3–7% in the short or medium term from the most intense removal of harvesting residues.

Mycorrhizal can be important for tree growth and survivability through enhanced nutrient and water uptake for hardwood eucalyptus species, and softwood pine species (Ortega et al. 2004, Chen et al.

2006). Mycorrhizal associations also develop naturally in native eucalypt forests and have been shown to develop quickly after fire (Warcup 1991). Declining crown health of eucalypts has been associated with mycorrhizal associations (Horton et al. 2013, Ishaq et al. 2013) but their role in causality is unclear and may be related to the long absence of fire.

Populations of natural enemies of key pests can provide a benefit to forestry operations through controlling pest populations and preventing tree damage and mortality. Studies have assessed different methods for maintaining populations of natural enemies of pests through minimising the use of broad-spectrum insecticides, notably α-cypermethrin. These methods include the adoption of an integrated pest management approach which considers populations of natural enemies as well as pest population before deciding on the need and timing of any spraying (Elliott et al. 1992), the use of alternative pesticides (Elek et al. 2004, Elek and Wardlaw 2013) and managing plantations to support higher diversity / abundance of natural enemies (Steinbauer et al. 2006, Boesing et al. 2017).

Severity of threat (biodiversity): Climate change is likely to have numerous effects on the services provided by biodiversity although there is high uncertainty associated with this risk pathway.

Climate change could affect both the timing of phenology and the spatial distribution of many species, including pollinators. These shifts could create mismatches between trees and pollinators with potential negative effects for ecosystem function and diversity.

Climate change could also affect the landcover and vegetation composition of forests, through changes to water availability, drought events, temperature shifts, changes in soil quality, and impacts from fire, weeds and pests and diseases. These myriad changes could have impacts on seed bank persistence into the future and hence impact on the availability and genetic diversity (Ooi 2012). For example, higher soil temperatures could accelerate the decline of seed viability, and changes to rainfall season may lead to losses of seed bank longevity. Higher temperatures are also likely to produce increased fire frequency, more frequent hot, dry conditions will reduce the activity of the soil microbial community and slow down the decomposition of litter and harvest residues (Shammas et al. 2003).

LINKS TO OTHER RISKS	EXPLANATION
Temperature (dependency risk) Section 3.4	• Biodiversity risk can be affected by changes in temperature. For example, it can alter phenological processes, such as flowering, fruiting (Beaumont et al. 2015, Rawal et al. 2015b, a) and seed set, and other important life-cycle events, such as germination and early growth.
Bushfire (dependency risk) Section 3.5	• Biodiversity risk and bushfire risk interact. For example, Fires can affect forest biodiversity and forest functioning. In addition, harvest residues provide fuel for bushfires and quick microbial decomposition of that residue can reduce fire risk. Transitions to alternative vegetation states/structures could also result in a positive flammability feedback (Coppoletta et al. 2016, Tepley et al. 2018, Burton et al. 2019).
Storms and floods (impact risk) Sector 3.7	• Biodiversity risk can be affected by storms through changes to species populations or forest functioning.
Soil quality (dependency/impact risk) Section 3.8 and 3.9	• Soil quality risk is linked to soil biodiversity and vegetation biodiversity. For example, forestry activities e.g. harvesting and chemical use can affect soil condition and soil biodiversity (Yasmin and D'Souza 2010). Changes in soil biota associated with forestry operations can affect nutrient and carbon cycling in forest soils and physical characteristics such as density, thereby affecting soil quality.
Weeds (dependency/impact risk) Section 3.14 and 3.15	• Biodiversity risk can be affected by weeds. For example, weeds can have indirect impacts on forests through changing species composition, influencing biodiversity and the dynamics and functioning of the forests. In addition, the spread of weeds associated with forestry operations presents a risk to the biodiversity of remnant vegetation and water courses.
Pests and diseases (dependency/impact risk) Section 3.16 and 3.17	• Biodiversity risk can be affected by pests and diseases. Certain pests and diseases can spread from forestry areas or through forestry activities and affect the biodiversity and functioning of forests.

MATERIALITY

SOFTWOOD PLANTATIONS	MODERATE

- **Degree of dependency: Moderate.** Natural enemies of pests are important for controlling pest populations and while insecticides are available which are effective the application is an additional business cost and the use of such insecticides is discouraged under FSC certification and can be toxic to aquatic fauna and socially unacceptable. Other services from biodiversity are either not applicable to softwood plantations (e.g. pollination) or a low risk (e.g. microbial decomposition and mycorrhizae).
- **Severity of threat: Moderate.** The high level of uncertainty regarding the future impacts of climate change on services provided by biodiversity make this a moderate risk. For example, the rate of decomposition could slow in warmer and drier conditions and the effectiveness of natural enemies in controlling pests could decrease if pest distributions shift into regions outside the distribution of their natural enemies. Changes in regulation or insecticide resistance could increase reliance on populations of natural enemies of pests.

HARDWOOD PLANTATIONS	MODERATE

- **Degree of dependency: Moderate.** As for softwood plantations except for pollination services are required in some situations such as open-pollinated seed orchards.
- **Severity of threat: Moderate.** As for softwood plantations.

NATIVE FORESTS	MODERATE

- **Degree of dependency: Moderate.** As for hardwood plantations except for pollination services are required for wild seed.
- **Severity of threat: Moderate.** As for softwood plantations.

Risk mitigation options

Mitigation options include:

- For pollination it is possible to shift to closed pollination processes for generation of seed for hardwood plantations, or artificially increase pollinator numbers using commercial beehives to improve pollination rates.
- For natural enemies of pests, the risks can be minimising by reducing the use of broad-spectrum insecticides through integrated pest management or managing the estate to support a higher abundance of natural enemies of pests.
- For nutrient cycling the risks can be mitigated by mechanical chopper-rolling of slash.

3.13 Biodiversity (impact risk)

Definition: the risk that forestry activities may negatively affect biodiversity or habitats.

Principal pathway: Forestry activities can negatively affect biodiversity in a variety of ways, including through alteration of forest age structure, habitat fragmentation and loss, introduction of invasive species, visual, noise and other disturbance, direct mortality of species (planned or unplanned), damage to species and communities through chemical use, alteration of hydrological processes, and alteration of soil structure and biota. The key risks relate to (1) direct or indirect impacts on biodiversity values as a result of forestry activities, and (2) community concerns about effective management of biodiversity values and (3) meeting regulatory requirements for habitat and biodiversity protection.

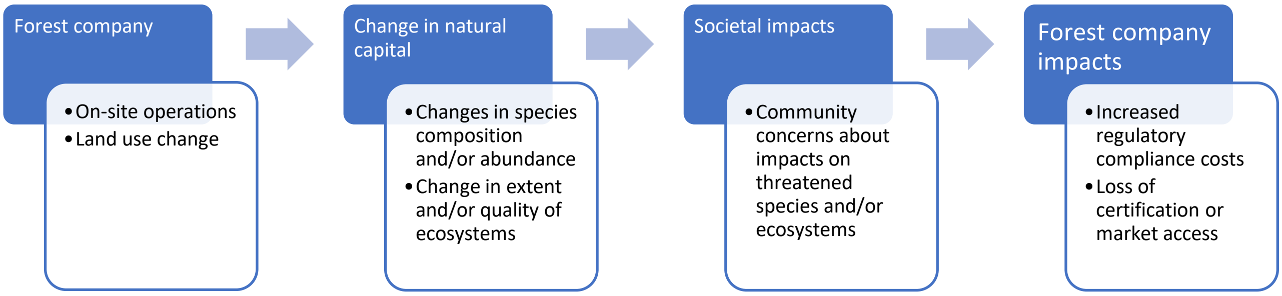

Figure 3-16 Causal pathway describing risks arising from the impact of forestry companies on biodiversity

Evidence

Degree of impact (biodiversity): Australian forests provide a home for at least 2,486 species of native animals and 16,836 species of native plants, of which 1,420 species are listed as threatened under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) (ABARES 2018). Native forestry has the capacity to negatively impact on biodiversity. It can alter forest age structure by increasing the abundance of younger forest and hence reducing the abundance of mature habitat that is important for species that require nesting hollows, feed on flowers and fruits, or forage on bark (Brown 1996, Koch et al. 2012, Balmer 2016). Hingston and Grove (2010) highlight the importance of maintaining old-growth forest amongst the production forest landscape for the succession of bird communities. Lefort and Grove (2009) show the impacts of different silviculture systems on birds and Baker et al. (2009) on beetles: in both studies, aggregated retention silviculture sustained greater numbers of mature forest bird communities and beetle populations.

Establishment and harvesting operations can also affect species composition and abundance. Studies on clearfelling have shown an impact on species composition and abundance (Fedrowitz et al. 2014). The regeneration of areas of forest that are disturbed (by harvesting) has been shown to be influenced by the distance to mature forest, with disturbed areas closer to mature forests experiencing more substantial re-establishment of both flora (e.g. bryophytes (Baker et al. 2016)) and fauna (e.g. beetles (Fountain-Jones et al. 2015)). A review by Baker et al. (2013) showed that distance to mature forest affects re-establishment of biodiversity after logging for all biodiversity groups but the scale of re-establishment varied with the dispersal capacity of the species (Hingston et al. 2014) and with the qualities of retained habitat and suitability of habitat conditions.

Plantation management practices can likewise negatively impact on biodiversity values. Harvesting practices remove habitat and can affect landscape connectivity (Hunter Jr 1990, Brockerhoff et al. 2008). Site preparation can damage soil structure and soil organic matter content, and can impact on soil macro- and micro-organisms. Use of chemicals such as herbicides, pesticides and fertilisers can have impacts on biodiversity through changes in habitat structure, direct toxicity, and accumulation of toxins within soil or food chains. Overall, however, plantation forestry may enhance biodiversity values relative to alternative land uses, particularly in regions where natural forest is highly fragmented (Brockerhoff et al. 2013). There is good evidence that plantation forests can provide valuable habitat and contribute to the conservation of biodiversity and landscape connectivity (Brockerhoff et al. 2008), although the role of plantations in contributing to broader biodiversity values remains contentious, and the values will generally be low compared with native forest (Kanowski et al. 2005). Plantation forests can play a role in protecting native forest remnants in agricultural landscapes from biodiversity declines triggered by edge-effects (MacHunter et al. 2006) and contribute to catchment-level tree cover needed to maintain healthy aquatic ecosystems (Magierowski et al. 2012). The habitat value of plantation forests revolves around characteristics such as age structure, successional processes and spatial and vertical heterogeneity. Generally, older plantations provide better habitat for forest species than younger plantations (Brockerhoff et al. 2008).

Severity of consequences (biodiversity): Impacts of forestry practices on biodiversity are managed under a range of instruments, including Commonwealth legislation such as the EPBC Act, state legislation and codes of practice, Regional Forest Agreements (RFAs) and voluntary certification schemes (e.g. the Forest Stewardship Council certification scheme). While the EPBC Act provides the overall legal framework for management of Australia's nationally and internationally important biodiversity, section 38 of the Act exempts forestry operations carried out in accordance with an RFA from the assessment and approval requirements of Part 3 of the Act. This has the effect of making state legislation the principal legal framework for protection and management of biodiversity impacts in the majority of Australia's production forests, where these are covered by RFAs. In Tasmania, the Forest Practices Act 1985 provides the overall legal framework for forest management, and the Threatened Species Protection Act 1995 and the Nature Conservation Act 2002 provide specifically for the management of threatened species and ecological communities, respectively (Tasmanian Government: Department of State Growth 2017). In practice, these are brought together in the Forest Practices Code, which requires the management of threatened species and communities with a strong focus on management prescriptions (Munks et al. 2020).[17]

There are special prescriptions that can be activated where threatened species or communities are found to be present, which may prohibit or restrict forestry activities in certain areas. There is also a risk of regulatory procedures being tightened in future. This could result from changes in scientific understanding of threats and/or impacts, policy changes, or changes in community perceptions. Community perceptions of forest management and issues around social licence to operate are complex and multifaceted and can change over time (Ford and Williams 2016, Kiley et al. 2017). Research in Tasmania found public preference for management approaches that protected native and old growth forests from logging whilst allowing intensified forest management elsewhere (i.e. land sparing) (Williams et al. 2012). In plantations grown in agricultural areas in Tasmania, the community recognised potential benefits of forestry activities for soil protection and employment, but were concerned about native vegetation and wildlife protection as well as water availability (Williams 2014, Ford and Williams 2016). In some regions, community pressure has resulted in restricted access

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[17] https://dpipwe.tas.gov.au/Documents/Final%20signed%20Procedures%20for%20the%20management%20of%20threatened%20species.pdf (accessed 17 April 2020).

to native forestry activities, for example the recently announced ban on old-growth logging and phase-out of all other native forest logging in Victoria by 2030.[18] Performance against environmental, social and economic outcomes may also be important in shaping public opinion.

LINKS TO OTHER RISKS	EXPLANATION
Temperature (dependency risk) Section 3.4	• Biodiversity risk can be affected by changes in temperature. For example, it can alter phenological processes, such as flowering, fruiting (Beaumont et al. 2015, Rawal et al. 2015b, a) and seed set, and other important life-cycle events, such as germination and early growth.
Bushfire (dependency risk) Section 3.5	• Biodiversity risk and bushfire risk interact. For example, Fires can affect forest biodiversity and forest functioning. In addition, harvest residues provide fuel for bushfires and quick microbial decomposition of that residue can reduce fire risk. Transitions to alternative vegetation states/structures could also result in a positive flammability feedback (Coppoletta et al. 2016, Tepley et al. 2018, Burton et al. 2019).
Storms and floods (impact risk) Sector 3.7	• Biodiversity risk can be affected by storms through changes to species populations or forest functioning.
Soil quality (dependency/impact risk) Section 3.8 and 3.9	• Soil quality risk is linked to soil biodiversity and vegetation biodiversity. For example, forestry activities e.g. harvesting and chemical use can affect soil condition and soil biodiversity (Yasmin and D'Souza 2010). Changes in soil biota associated with forestry operations can affect nutrient and carbon cycling in forest soils and physical characteristics such as density, thereby affecting soil quality.
Weeds (dependency/impact risk) Section 3.14 and 3.15	• Biodiversity risk can be affected by weeds. For example, weeds can have indirect impacts on forests through changing species composition, influencing biodiversity and the dynamics and functioning of the forests. In addition, the spread of weeds associated with forestry operations presents a risk to the biodiversity of remnant vegetation and water courses.
Pests and diseases (dependency/impact risk) Section 3.16 and 3.17	• Biodiversity risk can be affected by pests and diseases. Certain pests and diseases can spread from forestry areas or through forestry activities and affect the biodiversity and functioning of forests.

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[18] https://www.abc.net.au/news/2019-11-06/native-timber-logging-in-victoria-to-be-phased-out-by-2030/11678590 (accessed 8 April 2020).

MATERIALITY	
SOFTWOOD PLANTATIONS	MODERATE
• **Degree of impact**: **Moderate.** Harvesting of plantations can have substantial effects on biodiversity, for example, removing habitat, changing landscape connectivity, and changing soil conditions. In Australia, the majority of plantations are established on ex-agricultural or existing plantation land and so any negative impact from land use change is limited. • **Severity of consequences**: **Moderate.** There is already some concern regarding the impacts of harvesting on biodiversity. There is the potential for this to increase in the future as society becomes more aware of the biodiversity present in plantations and certain species become more reliant on the habitat provided by plantations due to other land use changes or climate change effects.	
HARDWOOD PLANTATIONS	MODERATE
• **Degree of impact**: **Moderate.** As for softwood plantations. • **Severity of consequences**: **Moderate.** As for softwood plantations.	
NATIVE FORESTS	HIGH
• **Degree of impact: High.** Harvesting in native forests, and in particular clearfelling, can potentially have a significant negative effect on biodiversity, affecting species abundance, habitat and damaging connectivity. • **Severity of consequences**: **High.** While consequences are managed through forestry codes of practice, there is considerable community concern which can halt operations and there is the possibility forestry operations could be further restricted in the future.	

Risk mitigation options

- Forest management practices for minimising impacts on biodiversity are well known, and widely embedded into Forest Practices Codes. Specific examples of management to reduce biodiversity impacts include: the management of native forests at the landscape scale, use of selective/retention management practices, and plantation operations such as species selection, minimising use of heavy machinery and chemicals, and landscape-level planning for siting of plantations.
- A further important element of risk mitigation is regular communication and engagement with the community, particularly those with strongly held beliefs about negative biodiversity impacts from forestry management.

3.14 Weeds (dependency risk)

Definition: the risk of lower productivity and increased costs due to competition from weeds.

Principal pathway: Weeds can affect both plantation forests and native forests by reducing productivity and/or increasing operational costs, and can necessitate the use of chemical herbicides (see section 3.11). In native forests, weeds can become locally dominant and reduce biodiversity and ecosystem function. In plantation forests, weeds can affect tree establishment and growth through outcompeting the trees for limited nutrient and water resources. Forestry operations as well as landscape-level and global changes can drive changes in the distribution and/or abundance of weeds.

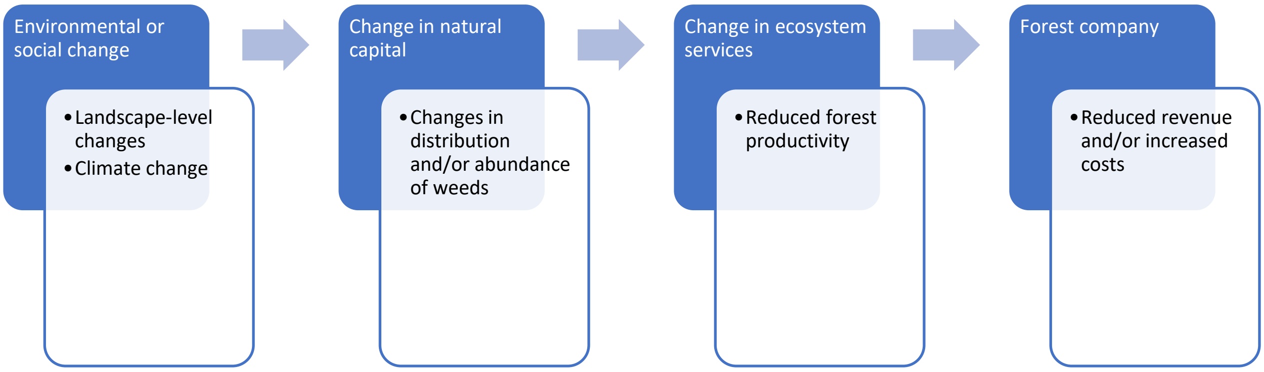

Figure 3-17 Causal pathway describing risks arising from the dependency of forestry companies on weeds

Evidence

Degree of dependency (weeds): Weeds can increase costs of plantation establishment (Williams and Wardle 2007), as well as affect the abundance and diversity of native vegetation (Grice 2006). Weeds are a threat to many different environments, competing with more desirable species for light, water and nutrients, and affecting biodiversity values, agricultural and forestry production and integrity of waterways (Vasic et al. 2012). Weeds can negatively affect ecosystems and their biodiversity (Steffen 2009a) and are typically characterised by fast growth, high dispersal ability, and high adaptability to different environments and conditions (Kriticos et al. 2010). The Australian State of the Forest report (ABARES2018) identifies the weed species with the most widespread adverse impacts on Australian forests as Gamba grass, bridal creeper, Mission grass, lantana, St John's wort, prickly pear, and blackberry.

For most regions of Australia weed species were reported as more damaging to native forest in conservation reserves and in multiple-use public forests, than to plantations. The Forestry Corporation of NSW (who manage the state forests) estimate that their expenditure on weed management in 2012/13 across their whole estate was $1.5 million (<1% of total company expenditure), with only a small proportion of this spent in their productive forests[19]. Plantation forests are at risk from native and cultivated plants that compete with the plantation trees. In plantations, controlling competition from weeds during early establishment has been shown to significantly improve growth and yield (Adams et al. 2003, Little et al. 2007, Eyles et al. 2012). Studies have shown that for softwood conifer species, the critical period is from planting up to age 3–5 years (Wagner et al. 1999), while for fast-

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[19] https://www.nrc.nsw.gov.au/PDF/Review%20Weed%20Management%20NSW/Submissions-Issues%20Paper/Submission%20-%20Forestry%20Corporation%20of%20NSW%20-%20Weed%20Management%20Review.pdf (accessed 1 December 2020)

growing hardwood eucalypt species, the critical period is shorter, up to approximately 20 months (Adams et al. 2003, Eyles et al. 2012). Weed management is often largely undertaken prior to tree planting and can be chemical (herbicides) and non-chemical (cultivation, slashing, burning and grazing). A range of herbicides can be used, depending on the site characteristics and weeds to be controlled.

Severity of threat (weeds): Predicted increases in temperature, variations in rainfall and increased frequency of extreme weather events such as droughts, storms and fires will have an impact on the development and spread of weeds and consequently have a flow-on effect to plantations and native forests. Weeds are likely to have similar physiological responses to climate change as other plants: some are expected to expand their distribution while others will retract, depending on individual species' responses to climate factors (Boulter 2012). In southern Australia, the projected increase in temperature and decrease in rainfall will potentially allow for the expansion of weed species currently restricted to the tropical north (Scott et al. 2008, Kriticos et al. 2011). In addition, disturbance from extreme weather events provides the opportunity for weeds to invade and establish (Scott et al. 2008, Scott et al. 2014). The typical weed characteristics of adaptability and quick development are likely to enable weeds to take advantage of higher disturbance frequency in native and plantation forests under climate change.

The reliance on chemical herbicide for weed control makes herbicide resistance a potential threat to plantation productivity. Herbicide resistance occurs from the repeated use of chemically similar herbicides to kill weeds. In addition, climatic factors can affect herbicide efficacy. These climatic factors can influence how herbicides penetrate the plant, how they are retained in the plant and the movement of the herbicide within the plant (Matzrafi et al. 2016).

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Water availability risk can be affected by weed competing with trees. • Weed risk (e.g. growth and distribution) just like other plants, can be affected by the availability of water.
Bushfire (dependency/impact risk) Section 3.5 and 3.6	• Weed risk can interact with bushfire risk. For example, some weeds are particularly flammable. There is a risk that soil disturbance associated bushfire will promote weed establishment.
Soil quality (dependency/Impact risk) Section 3.8	• Weed risk can be affected by soil quality and soil disturbance associated with forestry operations.
Fertiliser (dependency risk) Section 3.10	• Weed risk can be affected by fertiliser applications as it can alter their ability to compete with trees for nutrients, water and light.
Biodiversity (dependency/impact risk) Section 3.12 and 3.13	• Biodiversity risk can be affected by weeds. For example, weeds can have indirect impacts on forests through changing species composition, influencing biodiversity and the dynamics and functioning of the forests. In addition, the spread of weeds associated with forestry operations presents a risk to the biodiversity of remnant vegetation and water courses.

MATERIALITY

SOFTWOOD PLANTATIONS	**MODERATE**

- **Degree of dependency**: **Moderate:** weeds increase the cost of establishing plantations through competing for light, nutrients and water, however, the management for dealing with weeds is well established and the costs are only a small proportion of total annual expenditure.
- **Severity of threat**: **Moderate:** Climate change is likely to affect the distribution of weed species but there is considerable uncertainty about specifics. A general poleward shift of species is likely; however, this could result in an increased or decreased threat from weeds depending on location. Increased pesticide resistance could increase the cost of managing weeds in the future through switching to more expensive alternatives.

HARDWOOD PLANTATIONS	**MODERATE**

- **Degree of dependency**: **Moderate:** As for softwood plantations.
- **Severity of threat**: **Moderate:** As for softwood plantations.

NATIVE FORESTS	**MODERATE**

- **Degree of dependency: Moderate.** Weeds compete with native trees and can be a particular problem in native reserves or multiple-use forests, which can lead to increased management and control costs.
- **Severity of threat**: **Moderate.** As for softwood plantations.

Risk mitigation options

- Understand the existing presence of weeds and the characteristics of the site.
- Use a diversified approach toward weed management focused on preventing weed seed production and reducing the number of weed seed in the soil seedbank.
- Use different herbicides with different modes of action (Norsworthy et al. 2012) to reduce the risk of herbicide resistance.
- For native forest management: for established weeds, the priority is to prevent the spread into areas that are currently largely free of the weed. For potentially invasive species that have not become widely established, eradication may be possible.

3.15 Weeds (impact risk)

Definition: the risk that forestry activities increase the incidence, spread or impact of weeds.

Principal pathway: A forestry company may be affected by the impact of its activities on weed dispersal within and outside its boundaries, through increased weed control costs and community concerns.

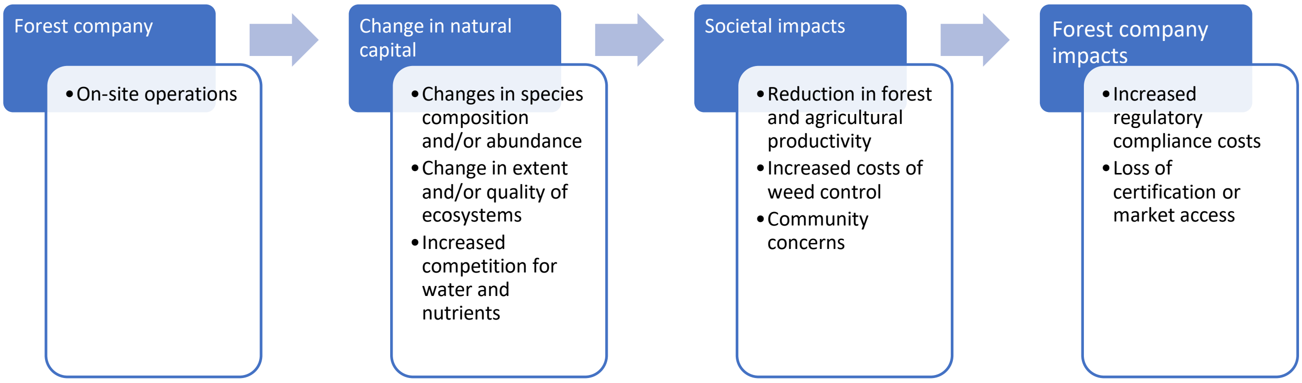

Figure 3-18 Causal pathway describing risks arising from the impact of forestry companies on weeds

Evidence

Degree of impacts (weeds): There are two principal pathways relevant to this impact risk: the establishment of wildlings or hybridisation associated with plantations; and the spread of weeds and weed seeds from the forestry estate or through the movement of machinery.

Softwood species have been identified as having a high environmental weed risk across Australia, as they are able to establish on cleared plantation sites and within adjacent, relatively undisturbed, native vegetation (Virtue and Melland 2003). Eucalyptus species are generally considered less of a weed risk in terms of wildling establishment (Calviño-Cancela and van Etten 2018), although plantations of these species may contribute to genetic pollution of adjacent native stands (Potts et al. 2003). Pollen dispersal can be more widespread than seed dispersal in these species, and many species can readily hybridise within taxonomic boundaries provided flowering is synchronous (Potts et al. 2003).

Accidental dispersal of weeds by humans, their vehicles and equipment has been well-documented for a range of production systems (van der Meulen and Sindel 2008), although published evidence of this is sparse for the forest sector in Australia. Movement of vehicles, machinery and people between sites can disperse weed seed and regenerative organs (van der Meulen and Sindel 2008, Ansong and Pickering 2013). Soil disturbance associated with roading, site establishment and harvesting activities provides ideal conditions for weeds to propagate. There are many examples of perennial and annual weed species dispersing along forestry access roads, and into both managed forest, conservation zones and adjacent agricultural land (e.g. pampas grass (Ducket 1989)).

Severity of consequences (weeds): Weeds associated with plantation forestry operations have the potential to affect adjacent native vegetation. There are concerns about adverse conservation outcomes from weed infestations and much attention in Australia has focused on movement of weeds into national parks and conservation areas, as well as agricultural land (Williams and West 2000, Virtue et al. 2004). There exist community concerns around weed incursions into neighbouring forested areas and waterways and the risk to biodiversity (Gawith et al. 2020). Concern from society and adjacent landowners has the potential to lead to further regulatory restrictions or to affect the social licence to operate, particularly for softwood plantations. In addition, voluntary certification standards such as the FSC (FSC Australia 2018) require forest managers to identify and implement effective actions to prevent negative impacts on environmental values and to mitigate and repair those impacts that do occur. The FSC states that forestry companies should only use exotic species when any invasive impacts can be controlled, and effective mitigation measures are in place. It is possible that more restrictive or costly practices could be imposed by regulation or voluntary certification schemes in future.

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Water availability risk can be affected by weed competing with trees. • Weed risk (e.g. growth and distribution) just like other plants, can be affected by the availability of water.
Bushfire (dependency/impact risk) Section 3.5 and 3.6	• Weed risk can interact with bushfire risk. For example, some weeds are particularly flammable. There is a risk that soil disturbance associated bushfire will promote weed establishment.
Soil quality (dependency/Impact risk) Section 3.8	• Weed risk can be affected by soil quality and soil disturbance associated with forestry operations.
Fertiliser (dependency risk) Section 3.10	• Weed risk can be affected by fertiliser applications as it can alter their ability to compete with trees for nutrients, water and light.
Biodiversity (dependency/impact risk) Section 3.12 and 3.13	• Biodiversity risk can be affected by weeds. For example, weeds can have indirect impacts on forests through changing species composition, influencing biodiversity and the dynamics and functioning of the forests. In addition, the spread of weeds associated with forestry operations presents a risk to the biodiversity of remnant vegetation and water courses.

MATERIALITY

SOFTWOOD PLANTATIONS	MODERATE

- **Degree of impact**: **Moderate.** Impacts include the spread of pine wildlings, in addition to the accidental dispersal of weeds from humans, vehicles and machinery.
- **Severity of consequences**: **Moderate.** There is concern about weed incursion into adjacent native vegetation, into conservation areas and into private property, and a possibility of increased regulation and/or certification requirements in future.

HARDWOOD PLANTATIONS	MODERATE

- **Degree of impact: Moderate.** Hardwood plantation species may contribute to genetic pollution of adjacent native stands.
- **Severity of consequences**: **Moderate.** As for softwood plantations.

NATIVE FORESTS	LOW

- **Degree of impact**: **Low.** Accidental spread of weeds is possible, although native forestry activities are reasonably well contained and regulated.
- **Severity of consequences**: **Moderate.** As for softwood plantations.

Risk mitigation options

Mitigation options are limited but can be very effective, and include:

- Chemical or physical control
- Washing down vehicles to reduce weed seed dispersal

Biological control agents exist for some weeds such as boneseed and blackberry – although effectiveness has been limited.[20]

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[20] https://www.environment.gov.au/biodiversity/invasive/weeds/publications/guidelines/wons/pubs/c-monilifera-monilifera.pdf and https://vicblackberrytaskforce.com.au/biological-control/ (accessed 30 March 2020)

3.16 Pests and diseases (dependency risk)

Definition: the risk of lower productivity, tree mortality and increased costs due to pests and diseases.

Principal pathway: Both plantation forests and native forests are at risk from pests and diseases. Pests and diseases can affect tree growth and survival of native and non-native forestry species. Forestry operations as well as landscape-level and global changes can drive changes in the distribution and/or abundance of pests and diseases.

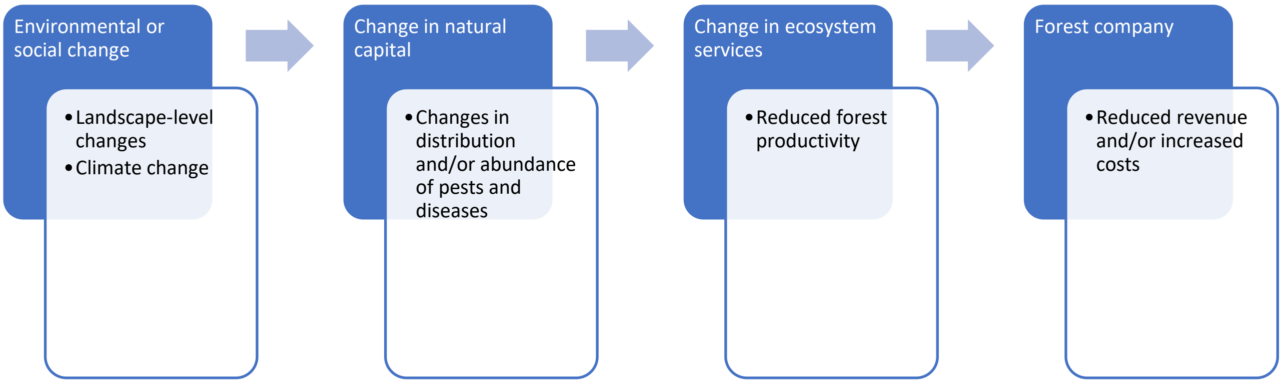

Figure 3-19 Causal pathway describing risks arising from the dependency of forestry companies on pests and diseases

Evidence

Degree of dependency (pests and diseases): Major pest species of Australian plantations and native forests can be categorised as defoliating insects and fungi, stem borers, and stem and root fungi. The impact of damage on growth and survival of native and non-native forestry species is well documented (Carnegie and Ades 2003, May and Carlyle 2003, Loch and Matsuki 2010, Carnegie and Bashford 2012, Smith et al. 2017). The key species currently responsible for damage in eucalypt plantations include Mycosphaerella leaf disease, Gonipterus leaf weevil, Autumn gum moth, Chrysomelid leaf beetles, and in longer rotation eucalypt plantations, stem borers such as *Phorocantha* (Pinkard et al. 2017). Similarly, exotic pest incursions into Australia have affected non-native plantations, including *Essigella californica*, *Sirex noctillio* and *Ips grandicollis* (Bungey 1966, Carnegie et al. 2006, Kimber et al. 2010). All of these species are known to reduce production and/or cause tree mortality.

Browsing of tree seedlings by mammalian herbivores is a worldwide problem and it can affect the short-term survival and the long-term productivity of forests. The severity of the defoliation is a key indicator of the effect on survival and growth. Studies in *Eucalyptus* plantation forests have shown that total defoliation of the crown resulted in long-term volume losses of 71-97% due to substantial mortality and poor growth (Wilkinson and Neilsen 1995). Heavily browsed seedlings that survived suffered poor growth due to their failure to achieve dominance over other competing vegetation. The timing of defoliation can also affect long-term productivity, with losses in spring resulting in lower overall volume growth (Wilkinson and Neilsen 1995).

Pathogen infestations can also result in tree mortality as well as lost production. For example, the fungal pathogen myrtle rust is now widespread across Australia and has the potential to damage many myrtaceous species (including eucalypts) (Carnegie et al. 2016). The current impact so far is small for *Eucalyptus* species in general and for the plantation industry (ABARES 2018), however, effects are being seen across a number of native species (Carnegie and Pegg 2018).

The sensitivity of plantations to pests and diseases compared to native forest can vary for a number of reasons. Plantations are more vulnerable to pests and disease when clones and hybrids of low genetic diversity encounter a pest or pathogen they are highly susceptible to (Andjic et al. 2019). Insects and fungi that are generally found in low numbers in native forests have become pests of eucalypt plantations (Carnegie et al. 1994, Loch and Floyd 2001). Silvicultural activities such as fertilising may increase the desirability of foliage to defoliators (O'Reilly-Wapstra et al. 2005). Finally, there is also a strong expectation of financial returns from plantations and that may lead to a lower tolerance of losses caused by pests and diseases compared with native forestry. Modelling studies suggest that high levels of defoliation could reduce final stand volume of short rotation eucalypt plantations by as much as 40% (Pinkard et al. 2014a).

Some analyses of the economic impacts of pest outbreaks have been performed in Australia (Wardlaw et al. 2011, Cameron et al. 2018, Carnegie et al. 2018, Wardlaw 2019). For example, Carnegie et al. (2018) showed that substantial losses in plantation timber revenue could be expected from tree mortality due to pine wilt disease, even at low probabilities of establishment and low rates of spread and mortality—the expected present value of plantation timber revenue losses in south-east Queensland was A$6.9 million. The timing of when damage occurs can be important for the financial consequences. The economic impact is far greater for damage late in the rotation—when the trees are merchantable or when there is insufficient time to recover growth (Wardlaw et al. 2018)—than damage earlier in the rotation.

Severity of threat (pests and diseases): There are a number of ways in which the risks from pests and diseases might change in the future. For example: changes to the host trees (i.e. different genotypes, different species); new pests and pathogens introduced to Australia; different management options becoming available; pesticide resistance; changes in demand for final products (i.e. from wood fibre to solid wood); and climate change (Wardlaw 2019). Here we focus mainly on climate change as a threat, either directly through changes to climatic factors such as temperature, precipitation, and relative humidity (Sutherst et al. 2007), or indirectly through physiological changes in the host, changes to natural enemies and competitors and changes in stress factors such fire, drought and storms (Ayres and Lombardero 2000). An extensive review of the potential impact of climate change on plantation pests in Australia is provided by Pinkard et al (2014).

Drought has been consistently linked with heightened pest and disease activity, and the projected reductions in rainfall (in some parts of Australia) and higher temperatures (across Australia) may lead to increased drought risk and hence increased pest and disease risk. Numerous studies associate times of drought with tree mortality (Keith et al. 2012, Seaton et al. 2015). For example, the peak of the Millennium drought in southeast Australia (2006-7) coincided with increased prevalence of a whole suite of pests, particularly in *P. radiata* plantations (ABARES 2018). Seaton et al. (2015) reported an outbreak of wood-borer (*Phoracantha*) in drought-affected northern jarrah forest following the 2011 drought in Western Australia and Wills and Farr (2017) found that outbreaks of gum leaf skeletoniser were associated with long-term drying trends and anomalous autumn/winter droughts.

Unusually high rainfall is also associated with increased activity of several diseases. There is strong evidence of increased damage from Dothistroma needle blight around the world associated with El Niño events (Woods et al 2016). The reverse phase—La Niña—is associated with anomalously high summer rainfall in eastern Australia. The strong La Niña event in 2011 coincided with a severe epidemic of Teratosphaeria (Mycosphaerella) leaf disease in eucalypt plantations in Tasmania and

Victoria (ABARES 2018 p245). Another La Niña event in 1970-71 (Hill et al. 2009) was associated with abnormally wet summers which triggered a *Phytophthora cinnamomi* dieback on the East Coast of Tasmania (Wardlaw and Palzer 1988). The timing of the 1970-71 La Niña event also spans the period of Calder Dieback in northwestern Tasmania (Wardlaw 1990).

Changes in both annual mean temperature and temperature extremes are important for pest populations (Ayres and Lombardero 2000). For a range of endemic pests of eucalypt plantations in Australia, for example, warmer annual mean temperatures are expected to increase the number of generations per year and the length of the damage season, as well as reducing winter mortality (Old and Stone 2005, Pinkard et al. 2009). This may result in more severe and prolonged outbreaks and consequent damage to eucalypt stands. Warmer and drier conditions in forests are predicted to particularly facilitate insect disturbances (Seidl et al. 2017). Ambient temperature is also the main regulator of the life cycle process of many pathogens; water and wind play important roles in the dispersal of spores; and various insects, functioning as vectors, contribute to the spread of pathogens. Increasing winter temperatures are expected to facilitate range expansions of pests to higher altitudes and latitudes (Burdon et al. 2006). Extreme high temperatures may also reduce survival and growth of insect and fungal species if their thermal limits are exceeded (Burdon et al. 2006); however, many of these species possess high thermal plasticity, and may be able to adapt to high temperature events. Host trees that are stressed by temperature extremes may also be more vulnerable to pest damage (Pinkard et al. 2014b).

The risk to Australian forestry from exotic pests is seen to be increasing, despite international regulations and inspections programs (Lawson et al. 2018). Over the last 15 years, pest interceptions at the border have been increasing, associated with a simultaneous, rapid expansion in the quantity of imported material and travellers arriving in Australia (Carnegie et al. 2017, Lawson et al. 2018). Despite the increased introduction of exotic pests and the associated risk the rate of establishment of non-native forest pests has remained relatively constant in Australia, accumulating at a rate of about two per year (Nahrung and Carnegie 2020). Exotic forest pests are extremely likely to continue to establish in Australia, and some of these will severely impact forest productivity and lead to tree mortality. The reliance on chemical pesticides for pest and disease control makes pesticide resistance a potential threat to plantation productivity. Climatic factors can affect pesticide efficacy. Reduced pesticide sensitivity has already been shown under climatic changes such as elevated temperatures and CO_2 enrichment (Matzrafi 2019).

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Water availability risk can be confounded by pests and diseases. Drought can make trees more susceptible to other stressors such as pests and diseases and vice-versa. The impact of forestry activities on the incidence or impact of pests and diseases can be modified by reduced water availability. Some species, such as stem borers, are attracted to water stressed trees. Other species, such as leaf fungi, require moisture to germinate and hence populations may decline.
Temperature (dependency risk) Section 3.4	• Pests and disease risk can be affected by changes in temperature and extreme high temperatures can affect the survival and spread of insect and fungal species.
Bushfires (dependency/impact risk) Section 3.5 and 3.6	• Pests and diseases risk interacts with bushfire risk. For example, pests and disease tree mortality can increase the fire risk, and in addition, fire can damage trees and make they more susceptible to pests and diseases.
Storms and floods (dependency risk) Section 3.7	• Pests and disease risk and storm event risk interacts. For example, storm events can damage trees and make them more susceptible to pests and disease, in addition, trees already suffering from pests and disease damage may be more susceptible to storm damage.
Biodiversity (dependency/impact risk) Section 3.12 and 3.13	• Biodiversity risk can be affected by pests and diseases. Certain pests and diseases can spread from forestry areas or through forestry activities and affect the biodiversity and functioning of forests.

MATERIALITY

SOFTWOOD PLANTATIONS	HIGH

- **Degree of dependency**: **High** Substantial losses in timber revenue could occur from tree mortality if thresholds of defoliation are reached.
- **Severity of threats**: **High.** Climate change may affect pest distribution and abundance directly and it may also affect tree susceptibly to pests and diseases. There is both a considerable threat and considerable uncertainty which makes this highly material. Threats from exotic pests and disease are also seen to be increasing and pesticide resistance could alter the efficacy of current management practices.

HARDWOOD PLANTATIONS	HIGH

- **Degree of dependency**: **High**: as for softwood plantations.
- **Severity of threat**: **High:** as for softwood plantations.

NATIVE FORESTS	HIGH

- **Degree of dependency**: **Moderate**: Native forests are more resilient to pests and diseases than plantations due to higher species and genetic diversity.
- **Severity of threat**: **High:** as for softwood plantations.

Risk mitigation options

- *Integrated pest management*: Pest surveillance is used in some parts of the forest industry as a way of tracking changes in pest species distribution and abundance. Long term monitoring provides the basis for more targeted control measures and supports modelling of pest risk and likely impacts (Wardlaw et al. 2011).
- *Biological control:* There has been a long-term biological control program for *Sirex noctillio* that uses a nematode, *Beddingia siricidicola*. It has been effective in controlling the pest under most circumstances (Carnegie and Bashford 2012). A biological control agent also has been introduced to help control *Esigella californica: Diaretus essigellae* (Kimber et al. 2010). *Baccilus thuringiensis* is applied in some situations as a control agent for chrysomelid beetles
- *Use of tolerant germplasm or alternative species*: Genetics trials with *E. globulus* have demonstrated that there is genetic variation in resistance to Mycosphaerella leaf disease (Carnegie et al 1994). However, there is limited evidence of field deployment, with growers instead opting to change to a more tolerant species (Wardlaw 2001).
- *Forest hygiene:* Many pest species overwinter in the forests they feed on. Removing overwintering sites has been used successfully in the control of *Ips grandicollis* (Bungey 1966). Managing weeds and slash on the forest floor has potential to help in the management of other pest species.
- *Silviculture*: Fertilising with nitrogen has been demonstrated to promote faster crown recovery following defoliation from Mycosphaerella leaf disease (Wardlaw 2001). Early thinning has been used effectively in managing risk of *Esigella* outbreaks (May 2004).

3.17 Pests and diseases (impact risk)

Definition: the risk that forestry activities increase the incidence, spread or impact of pests and diseases.

Principal pathway: The existence of forested areas within a landscape can provide habitat for pests and diseases which may then affect surrounding areas. Forestry operations may also contribute to the spread of pests and diseases. This can reduce forest and agricultural productivity or affect human health and result in costs to society, which may in turn result in increased regulatory compliance costs for forestry companies.

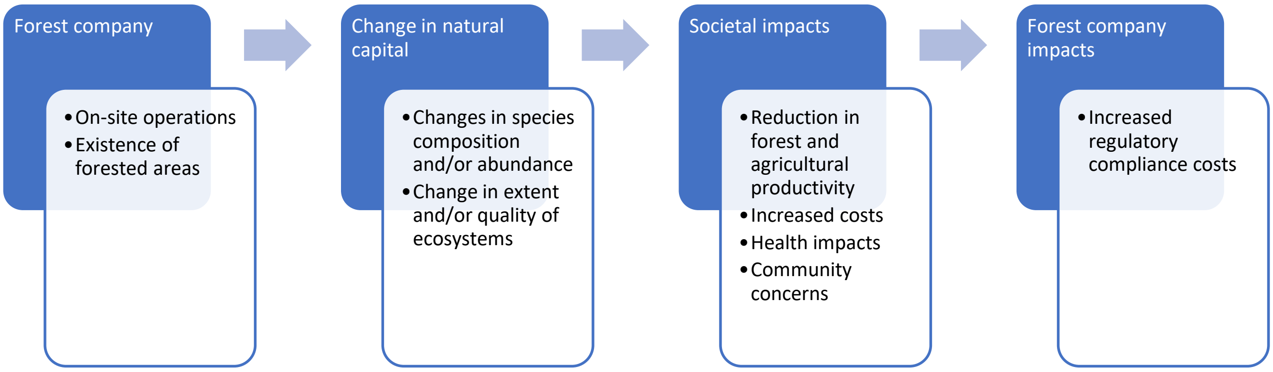

Figure 3-20 Causal pathway describing risks arising from the impact of forestry companies on pests and diseases

Evidence

Degree of impact (pests and diseases): Forestry operations can contribute to the spread of pests and diseases, for example through the movement of vehicles, machinery and people between sites. This has been linked to the spread of soil-borne pathogens such as *Phytophthora cinnamomi* (Shearer and Smith 2000). In addition, plantations can facilitate the introduction of non-native insects through the growth of species which are exotic to Australia or to regions within Australia, for example, when *Eucalyptus globulus* is grown outside its native distribution of south-eastern Australia and Tasmania (Grimbacher et al. 2011). As well as vectoring pathogens, another collateral impact of forestry activity is artificial elevation of an established pest or pathogen. For example, myrtle wilt, which occurs naturally in undisturbed rainforest, can spread locally following disturbance from forestry roading or harvesting (Elliott et al. 2005). Monoculture plantations can also increase pest and disease populations by providing a uniform source of food and optimal conditions which can result in more frequent and severe epidemics (O'Reilly-Wapstra et al. 2005).

Forested areas provide habitat for a range of native and non-native browsing mammals, some which may be viewed as pests in adjacent agricultural or urban landscapes as they can compete with domestic livestock and/or damage crop production. Examples include rabbits (Norbury and Norbury 1996), deer (Davis et al. 2016), wallabies and kangaroos (Hill et al. 1988, Arnold et al. 1989). A recent review of damage to agricultural production showed that such damage is well known for a variety of browsing mammals, but that the evidence is often anecdotal and quantitative estimates of the damage are lacking (Latham et al. 2020).

Land use change and disturbance has also been linked with emerging infectious diseases. McFarlane et al. (2013) find that 22% of new infectious diseases in Australia were associated with land use change and native vegetation change. This was most frequently where natural landscapes have been removed or replaced with agriculture, plantations, livestock or urban development.

Severity of consequences (pests and diseases): Pests and diseases are not just a concern for forestry companies (see section 3.16), they can also be a concern for local communities. As an example, giant pine scale is an exotic pest that was introduced to Australia in 2014 and caused damage to *Pinus radiata* in metropolitan areas on private land which were destroyed using the authority of the biosecurity regulations (Carnegie et al. 2017). Trees on or adjacent to agricultural land can be perceived to increase pest pressure on the agricultural land which may cause concern among neighbouring landowners or may affect farmers decisions regarding agroforestry (Fleming et al. 2019). There are also concerns about adverse conservation outcomes resulting from pests and pathogens that have broad host ranges extending beyond commercial forestry species. For example, forestry activities have contributed to the introduced the pathogen, *Phytophthora cinnamomi*, into previously disease-free areas. *Phytophthora cinnamomic has* caused disease in native species, including species of high conservation significance such as the jarrah forests of Western Australia (Shearer and Smith 2000). Voluntary certification standards such as the FSC (FSC Australia 2018) require forest managers to identify and implement effective actions to prevent negative impacts on environmental values and to mitigate and repair those impacts that do occur, this includes the suppression of pests and diseases. It is possible that more restrictive or costly practices could be imposed by regulation or voluntary certification schemes in future.

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Water availability risk can be confounded by pests and diseases. Drought can make trees more susceptible to other stressors such as pests and diseases and vice-versa. The impact of forestry activities on the incidence or impact of pests and diseases can be modified by reduced water availability. Some species, such as stem borers, are attracted to water stressed trees. Other species, such as leaf fungi, require moisture to germinate and hence populations may decline.
Temperature (dependency risk) Section 3.4	• Pests and disease risk can be affected by changes in temperature and extreme high temperatures can affect the survival and spread of insect and fungal species.
Bushfires (dependency/impact risk) Section 3.5 and 3.6	• Pests and diseases risk interacts with bushfire risk. For example, pests and disease tree mortality can increase the fire risk, and in addition, fire can damage trees and make they more susceptible to pests and diseases.
Storms and floods (dependency risk) Section 3.7	• Pests and disease risk and storm event risk interacts. For example, storm events can damage trees and make them more susceptible to pests and disease, in addition, trees already suffering from pests and disease damage may be more susceptible to storm damage.
Biodiversity (dependency/impact risk) Section 3.12 and 3.13	• Biodiversity risk can be affected by pests and diseases. Certain pests and diseases can spread from forestry areas or through forestry activities and affect the biodiversity and functioning of forests.

MATERIALITY

SOFTWOOD PLANTATIONS	LOW

- **Degree of impact: Moderate.** Plantation forestry activities can spread pests and diseases across the landscape through dispersion, for example, through the movement of vehicles, machinery and people between sites. The impact and damage from pests and diseases spreading can be substantial (e.g. *Phytophthora*), however, management and control practices are well known (e.g. washing down machinery).
- **Severity of consequences: Low.** Pest and disease dispersal into agricultural landscapes, native vegetation and conservation areas can generate concern, but the probability of significantly increased regulatory or certification compliance costs is considered to be low.

HARDWOOD PLANTATIONS	LOW

- **Degree of impact: Moderate.** As for softwood plantations.
- **Severity of consequences: Low.** As for softwood plantations.

NATIVE FORESTS	LOW

- **Degree of impact: Moderate.** Native forestry disturbance elevates the level of activity of already-present pests or diseases, e.g. myrtle wilt, and can further imperil susceptible species that are already of high conservation significance. Forestry can introduce soilborne pathogens into new areas.
- **Severity of consequence: Low.** As for softwood plantations.

Risk mitigation options

Minimising the risk of pests and disease spread is managed through prescriptions in forest practices plans. Options to reduce the risk of spreading pests and diseases as a result of forestry operations include:

- *Management areas*: Areas are designated for containing species or protecting communities that are particularly susceptible to the pathogen, for example, *Phytophthora* management areas.
- *Forest hygiene:* The risk of spreading pests and diseases can be reduced through hygiene measures, such as machinery hygiene practices and plans for infrastructure and operations machinery and equipment. Managing weeds and slash on the forest floor has potential to help in the management of other pest species.

3.18 Energy (dependency risk)

Definition: the risk of lower productivity and increased costs due to inefficient use of energy and/or higher prices of energy inputs (Ascui and Cojoianu 2019a).

Principal pathway: Energy purchases form part of the cost base of forestry companies, which depend on inputs of energy, usually derived from fossil fuels, for transportation and to power harvesting and processing equipment, and to a lesser extent, office-based activities. (They also depend on renewable energy in the form of sunlight to grow biomass, but this is not considered further as it is in abundant supply). The cost of fossil fuels is determined mainly by factors that have little to do with natural capital (e.g. geopolitics, technology, market forces and taxes) and therefore the risk associated with energy price increases for these reasons is not considered further in this analysis. There is a risk, however, associated with the efficiency of energy use, over time and/or relative to competitors, as less efficient use of energy will increase a company's exposure to this dependency.

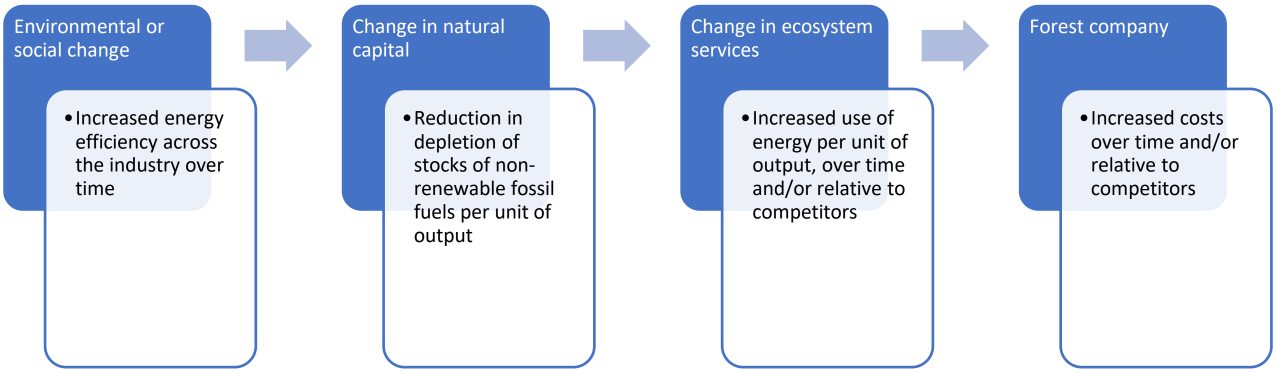

Figure 3-21 Causal pathway describing risks arising from the dependency of forestry companies on energy

Evidence

Degree of dependency (energy): Forestry operations depend on energy in several ways. A cradle-to-gate life cycle assessment (LCA) of Australian softwood plantations and native forests found that total energy used in production of wood products was 239 MJ/m^3 for plantations and 527 MJ/m^3 for native forests (May et al. 2012). The largest component of total energy use was log haulage (46% and 45% respectively), followed by harvesting and chipping (29% and 44% respectively). Most energy inputs to forestry operations come in the form of diesel (172 MJ/m^3 and 355 MJ/m^3 or 72% and 67% of total energy use, respectively) (May et al. 2012). For forestry companies, fuel can be a substantial expense, for example, Forestry Corporation NSW estimate that fuel accounts for between 11% and 15% of harvest costs (Independent Pricing and Regulatory Tribunal 2017). However, despite this link to business costs there appears to be little correlation between fuel prices and the price of wood fibre over time, with studies showing that the price of wood products in the market is dominated by supply and demand of the products rather than fuel prices (Coutu 2019).

Severity of threat (energy): New technologies and energy efficient transport and harvesting vehicles and machinery are improving the overall energy efficiency of harvesting. For example, Forestry Corporation NSW have cut diesel use by 25% between 2012/13 and 2018/19 whilst maintaining similar amounts of harvested timber (Forestry Corporation NSW 2019). Improvements in harvesting efficiency can help reduce the threat from fuel price volatility which affects business costs. Those companies which do not improve energy efficiency face the threat of being outcompeted by more efficient companies and also being a less attractive investors looking for social and environmental impacts (Global Impact Investing Network 2018).

LINKS TO OTHER RISKS	EXPLANATION
Greenhouse gas (impact risk) Section 3.19	Greenhouse gas risk is linked to energy consumption and fossil fuel use.

MATERIALITY	
SOFTWOOD PLANTATIONS	**LOW**
• **Degree of dependency**: **Moderate:** For forestry companies, fuel can be a substantial expense associated with harvesting operations. • **Severity of threat**: **Low.** Energy efficiency improvements from competitors in the industry could mean some forestry companies are unable to compete or are less attractive investors looking for social and environmental impacts.	
HARDWOOD PLANTATIONS	**LOW**
• **Degree of dependency**: **Moderate.** As for softwood plantations. • **Severity of threat**: **Low.** As for softwood plantations.	
NATIVE FORESTS	**LOW**
• **Degree of dependency**: **Moderate:** Fuel use is higher in native forestry than plantations for both harvesting and haulage. • **Severity of threat**: **Low.** As for softwood plantations.	

Risk mitigation options

The main mitigation options relate to investment in energy-efficient harvesting and haulage assets and the use of renewable energy sources.

3.19 Greenhouse gas emissions (impact risk)

Definition: the risk that emissions of greenhouse gases (GHGs) may be priced at higher levels in future, reflecting true costs of climate change, or that regulations will limit future GHG emissions.

Principal pathway: Forestry can affect concentrations of GHGs in the atmosphere by directly or indirectly causing emissions of GHGs, as well as their removal through biomass growth and sequestration of carbon in soils. Emissions attributable to a company can be related to a variety of operational activities as well as land use change (for plantations), while natural processes such as bushfires can affect both emissions and removals. Increasing concentrations of GHGs in the atmosphere contributes to climate change, raising community concerns which could lead to increased regulation or higher pricing of GHG emissions in future.

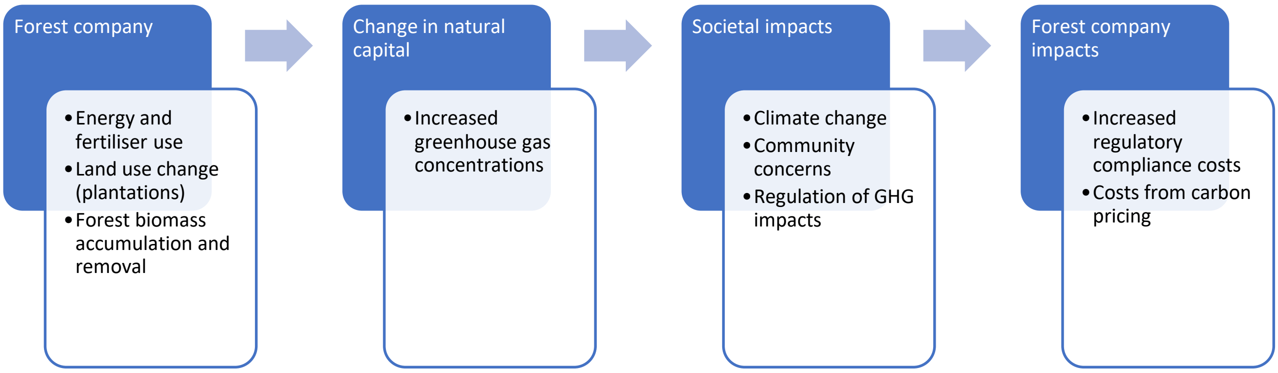

Figure 3-22 Causal pathway describing risks arising from the impact of forestry companies on greenhouse gas emissions

Evidence

Degree of impact (GHG emissions): GHG emissions typically associated with forestry operations include emissions associated with establishment, forest management and harvesting activities. While emissions associated with these activities will vary depending on site conditions, scale of operations and the machinery used, England et al. (2013) estimate that, in Australia, GHG emissions per unit wood production from native forestry (70.6 kg CO_2-e/m^3) are approximately 2.7 times higher than from softwood plantations (25.9 kg CO_2-e/m^3), primarily due to emissions of non-CO_2 GHGs (such as methane and nitrous oxide) from slash burning in native forestry (32.8 kg CO_2-e/m^3). For softwood plantations, operational emissions are dominated by log haulage (37%) and harvesting (21%, covering thinning, clearfelling and chipping), while for native forests, haulage (23%) and harvesting (21%) are also significant contributors, after slash burning (46%). Another significant difference between the systems is fertiliser and other chemical use, which accounts for 16% of softwood plantation emissions, but which is negligible for native forest operations. Fertiliser is used in plantation forestry to promote growth, and improve recovery following pest damage. Of particular concern are emissions of nitrous oxide, which has a global warming potential 265 times larger than that of CO_2. In addition to direct emissions, transportation and application of fertilisers also results in GHG emissions. Overall, operational emissions from softwood plantations averaged around 3.3% (range 1.6-4.7%) of the amount of sequestered carbon in an average log, compared with 7.3% (4.4-26%) for an average native hardwood log England et al. (2013). Because operational emissions are small relative to the total mass of sequestered carbon in harvested logs, the ratio between these is highly sensitive to wood density England et al. (2013), which, as we note elsewhere, can be affected by water availability, temperature and fertiliser use (see sections 3.1,3.4 and 3.10).

However, the above estimates are limited by some important assumptions.

1. The scope is limited to operational emissions up to the mill gate. Additional emissions may be associated with transport, further processing, use and disposal of wood products. Carbon stored in harvested wood products is eventually released back to the atmosphere, but the period of storage can vary from nil (instantaneous oxidation, for example through burning) to a few years for pulp and paper, to decades or even hundreds of years for wood used in buildings. In addition, wood used in buildings can substitute for carbon-intensive alternatives such as concrete and steel, and a variety of wood products can be used at end-of-life for energy production, potentially displacing fossil fuels. The end use of harvested wood products is therefore an important differentiating factor between forestry systems in their overall impact on greenhouse gas emissions (Ximenes et al. 2016). For example, hardwood plantations in Australia are almost exclusively used for pulplogs, whereas softwood plantations produce about one-third pulplogs and two-thirds sawlogs (ABARES2018). For native forests, the proportions vary, but in the five years from 2011-2016, a little over half of the annual harvest from Australian native forests was sawlogs, with the remainder being pulplogs (ABARES2018).
2. The estimates exclude all biogenic CO_2 emissions, including from unplanned fires, on the assumption that the forest system is in a steady state with respect to long-term forest carbon stocks. The actual balance between carbon sequestered in growing forest and soils, and GHGs emitted (through forestry operations, various natural processes, and oxidation of harvested wood products) can be affected by a variety of both planned and unplanned actions, such as harvesting/replanting rates, heatwaves (Wardlaw 2018) and bushfires[21], and depends on how each of these are measured, with respect to what baseline. Therefore, the assumption of a steady state with respect to long-term forest carbon stocks may not always hold true for all forests, and there are some indications of forests becoming net emitters rather than net sinks under climate change, particularly with increased incidence of tree mortality through drought and bushfires (Keith et al. 2014, Hubau et al. 2020). In general, carbon sequestered during regrowth can at best only offset emissions from natural processes and oxidation of wood products at end-of-life: meaning that ongoing operational emissions continue to contribute to global GHG concentrations.
3. The estimates also assume no changes in land use or forest management over time, such as plantation establishment on cleared agricultural land or the conversion of old-growth native forests to regrowth. While forest loss and degradation is a major source of GHG emissions globally, this is less relevant in an Australian context, as most states now prohibit or significantly restrict the clearing of native vegetation (ABARES2018), and conversion of native forests to plantations is not allowed under certification schemes (FSC Australia 2018). However, conversion of agricultural land to plantations may still occur in Australia, which could result in indirect land use change elsewhere to make up for lost agricultural production (Searchinger et al. 2008).

Severity of consequences (GHG emissions): There is currently no direct carbon pricing applied to forestry operational emissions in Australia, with the exception of projects receiving funding for net emission reductions/removals from the Commonwealth Emissions Reduction Fund, which must

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[21] Wardlaw, T. (*In Prep.*) Measuring a fire. The story of the January 2019 fire told from measurements at the Warra Supersite, Tasmania

deduct any operational emissions from calculated net emission reductions/removals.[22] These projects therefore effectively incur an opportunity cost equivalent to the current market price for Australian Carbon Credit Units (ACCUs), which is currently around A$15/t$CO_2$-e.[23]

Within Australia, the forestry industry is considered to be a net CO_2 sink (England et al. 2013), and globally, forests and afforestation are considered to be critical for GHG and climate change mitigation (IPCC 2018). This reduces the likelihood of carbon pricing being applied to Australian forestry GHG emissions in the short- to medium-term. However, given the scale of the global challenge to reach net zero GHG emissions by 2050[24], it is considered moderately likely that there will be some form of carbon pricing or tighter regulation of forestry GHG emissions in the longer term. For example, in New Zealand, forestry is included in the national Emissions Trading Scheme, meaning that forest owners are liable for reductions in carbon stock (although they also benefit from receiving credits for increases in carbon stock).[25] Certification schemes such as the FSC already require that forestry management activities maintain, enhance or restore carbon storage in the forest (FSC Australia 2018).

LINKS TO OTHER RISKS	EXPLANATION
Water availability (dependency risk) Section 3.1	• Greenhouse gas risk can be affected by water availability. For example, water availability is a key determinant of tree growth and affects the GHG sequestration rate of forests. Droughts have been associated with increased incidence of tree mortality and therefore GHG emissions.
Temperature (dependency risk) Section 3.4	• Greenhouse gas risk can be affected by temperature. For example, temperature is a factor in the greenhouse gas sequestration rate of forests.
Bushfires (dependency/impact risk) Section 3.5 and 3.6	• Greenhouse gas risk can be affected by fire from the significant greenhouse gas emissions that are associated with fires.
Soil quality (dependency/impact risk) Section 3.8 and 3.9	• Greenhouse gas risk can be affected by forestry activities which impact stored soil carbon and prevent the soil reaching its potential for carbon sequestration.
Fertiliser (dependency risk) Section 3.10	• Greenhouse gas risk can be associated with fertiliser use and its contribution to greenhouse gas emissions through the production, transportation and application of fertilisers.
Energy (dependency risk) Section 3.18	• Greenhouse gas risk is linked to energy consumption and fossil fuel use.

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[22] See http://www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-the-land-sector/Vegetation-methods (accessed 17 November 2020).

[23] http://www.cleanenergyregulator.gov.au/ERF/Pages/Auctions%20results/September%202020/Auction-September-2020.aspx (accessed 17 November 2020).

[24] https://unfccc.int/climate-action/race-to-zero-campaign (accessed 3 December 2020)

[25] https://www.mpi.govt.nz/forestry/forestry-in-the-emissions-trading-scheme/ (accessed 17 November 2020).

MATERIALITY

SOFTWOOD PLANTATIONS	LOW

- **Degree of impact: Low.** Direct operational emissions for Australian softwood production are low compared with native forestry and international estimates England et al. (2013), and almost two-thirds of production goes towards longer-lived wood products. Clearing of native forest for plantation establishment is no longer practiced.
- **Severity of consequences: Low** in the short to medium term, **Moderate** in the longer term.

HARDWOOD PLANTATIONS	MODERATE

- **Degree of impact: Moderate.** As for softwood plantations, but virtually all hardwood production goes towards short-lived fibre products.
- **Severity of consequences: Low** in the short to medium term, **Moderate** in the longer term.

NATIVE FORESTS	MODERATE

- **Degree of impact: Moderate.** Direct operational emissions for Australian native forest production are high compared with softwood plantations and international estimates England et al. (2013), and roughly half of production goes towards longer-lived wood products.
- **Severity of consequences: Low** in the short to medium term, **Moderate** in the longer term.

Risk mitigation options

Mitigation options revolve around reducing emissions, and improving communication about the balance between GHG emissions and carbon sequestration.

For the first, businesses could consider:

- Shifting to renewable energy sources where possible;
- Reducing fertiliser emissions by shifting to slow release, pelletised fertilisers and subsurface application methods; and
- Mechanical fuel management to reduce fire risk.

For the second, businesses could invest in life cycle analysis to track their emissions and sequestration. Life cycle analysis provides a consistent approach to assess total emissions associated with wood production and to determine the carbon footprint of wood products (England et al. 2013).

3.20 Other air emissions (impact risk)

Definition: the risk that other air emissions (such as particulates and volatile organic compounds) may be priced at higher levels in future, or regulations will limit future emissions.

Principal pathway: Forests can contribute to air pollution in two main ways: through emissions of particulates and other components of wood smoke from fuel reduction and regeneration burns, and as a major source of volatile organic compounds (VOCs) that contribute to the production of tropospheric ozone, a component of urban air pollution or ‘smog’. Air pollution has significant impacts on human health. This gives rise to a risk that such emissions could be regulated or priced in some way in future, thus possibly increasing operational costs or reducing revenue for forest businesses. ‘Pricing’ of these emissions could occur through reputational impacts or loss of social licence to operate, as well as more explicitly through regulation.

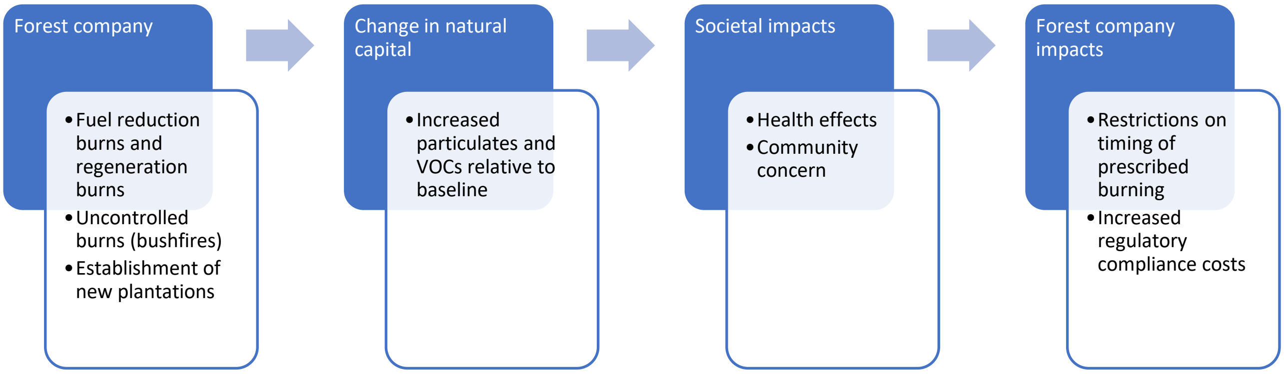

Figure 3-23 Causal pathway describing risks arising from the impact of forestry companies on other air emissions

Evidence

Degree of impact (other air emissions): The controlled use of fire in managed forests in Australia revolves around reducing fire hazard or promoting establishment through removal of harvest residue (plantation forests) or preparation of a seedbed (native forests) (Scott et al. 2012, McCaw 2013). In addition to this, both plantations and native forests are exposed to uncontrolled burns (bushfires) resulting from various causes, from lightning strikes to arson.

Burning forest biomass results in emissions of particulate matter and chemicals such as biogenic secondary organic aerosol compounds, and carboxylic acid and heteroatomic organic acids (Keywood et al. 2015, Iinuma et al. 2016, Keywood et al. 2016). Carboxylic acid compounds are largely a result of eucalypt VOC emissions (Iinuma et al. 2016). Particulates (especially those with diameters below 10 microns and 2.5 microns, known as PM10 and PM2.5, respectively) are the major source of public health issues associated with fire (Reisen and Brown 2006, Johnston et al. 2011, Johnston et al. 2012). All of these substances have been linked to acute or chronic respiratory conditions. PMs have also been linked to cardiovascular disease (Doctors for the environment Australia 2017).

Episodes of extreme air pollution in Australian cities are strongly associated with forest fires – for example, of the 52 days with PM$_{10}$ concentrations over the 99th percentile in Sydney between 1994 and 2007, 48 were associated with bushfire smoke, and similar patterns can be observed for other Australian cities (Paton-Walsh et al. 2019). The Victorian fires of 2006-07 resulted in PM$_{10}$ concentrations in Melbourne that exceeded 200 ug/g/m^3 (Keywood et al. 2015) – four times the recommended maximum concentration (Heywood et al 2016). Hazard reduction burns have also been found to significantly increase PM10 concentrations (Desservettaz et al. 2019), often with strong local impacts, due to being carried out at times of low wind speeds, which limits dispersion (Paton-Walsh et al. 2019).

Forests also contribute to the production of tropospheric ozone, an air pollutant formed by complex photochemical reactions between nitrogen oxides (NO_x) and VOCs in the presence of sunlight (Nguyen Duc et al. 2018). Tropospheric ozone pollution is typically only a significant problem in major metropolitan centres where there are large sources of NO_x, such as power stations, automobiles and other transport, and industrial combustion facilities. In such areas with high NO_x levels, ozone formation is often limited by the availability of VOCs (Paton-Walsh et al. 2019), which can come from a range of anthropogenic and/or biogenic sources. Sources of anthropogenic VOCs in Australia include domestic-commercial activities such as spray painters and dry-cleaners (54%), other commercial and industrial sources such as mining and chemical manufacturing (15%), and transport (31%),[26] while 90% of biogenic VOCs are emitted by plants and trees (Emmerson et al. 2016). A study of ozone formation in the Sydney greater metropolitan region found that biogenic VOC emissions greatly dominated anthropogenic VOC emissions (Nguyen Duc et al. 2018), while another modelling study found that if all biogenic VOCs were removed from the model, no ozone exceedance events occurred (Paton-Walsh et al. 2019). By illustration, Sydney experienced nine days between 2015 and 2017, and a further seven in 2018, which exceeded the national standard for ozone pollution (Paton-Walsh et al. 2019). Such implications cannot necessarily be generalised to other Australian cities due to the complex interplay between air chemistry and environmental factors that cause ozone pollution. However, south-eastern Australia is considered to be a global hotspot for biogenic VOC emissions due to the presence of large areas of forest, dominated by high-emitting eucalypt species (Emmerson et al. 2016).

Biogenic VOC emission rates from vegetation vary considerably between species and with environmental conditions (e.g. increasing with light, temperature and disturbance such as felling or pruning, and decreasing with water stress) (Owen et al. 2013, Emmerson et al. 2016). VOC emissions can also vary at different growth stages: for example, several studies of *Eucalyptus* species found that young trees have VOC emissions 3-5 times higher than adults (Emmerson et al. 2016) – however, a study of *Pinus pinea* found the opposite effect, with mature tree emissions twice that of young trees, suggesting that age-related differences are species-specific (He et al. 2000). In general, *Eucalyptus* species, and *E. globulus* in particular, are considered to be among the highest VOC emitting plants, although estimates of their emission rates may be biased by being based on young trees (He et al. 2000, Emmerson et al. 2016). Softwoods such as *Pinus radiata* also emit VOCs, but at an order of magnitude lower rates (Aydin et al. 2014). New hardwood plantations in areas surrounding major urban centres therefore have the potential to increase the baseline rate of biogenic VOC emissions, particularly in the early years of establishment, and thereby contribute to increased ozone pollution, with consequent health effects: for example, a study on Sydney estimated that ozone pollution contributed to 0.8% of all fatalities (Paton-Walsh et al. 2019).

Severity of consequences (other air emissions): There has been considerable community concern around the health impacts of smoke associated with forest fires (AFAC and FFMG 2015), and to a lesser extent, around the contribution of biogenic VOCs to urban ozone pollution (Paton-Walsh et al. 2019). In Australia, air quality is regulated primarily by state governments, coordinated under the National Environment Protection Council, which issues National Environment Protection Measures (NEPMs) in different areas, including ambient air quality. The Ambient Air Quality NEPM was made in 1998 and sets thresholds for various air pollutants (including particulates and ozone) affecting

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[26] https://soe.environment.gov.au/theme/ambient-air-quality/topic/2016/pollution-sources (accessed 24 March 2020).

ambient air quality that allow for the protection of human health and well-being.[27] However, the NEPM currently excludes smoke from bushfires and hazard reduction burns (Paton-Walsh et al. 2019), and does not directly require monitoring or control of biogenic VOCs.

To the best of our knowledge, there is no current regulatory restriction on the establishment of new plantations in peri-urban areas specifically on the basis of their contribution to biogenic VOCs. Such regulation might be possible in future, although the probability seems low, due to the complexity of the causal pathway and interactions with other environmental factors, including large emissions from existing forests. Higher temperatures due to climate change can be expected to increase ozone exceedances in future, via a number of causal factors including increased biogenic VOC emissions, but this may be offset to some extent by decreased biogenic VOC emissions from forests under more frequent water stress conditions.

LINKS TO OTHER RISKS	EXPLANATION
Bushfires (dependency/impact risk) Section 3.5 and 3.6	• Air emission risk can be affected by fire. For example, from the emissions of particulates and other air pollutants in smoke and dust from burnt areas.

MATERIALITY	
SOFTWOOD PLANTATIONS	**LOW**

- **Degree of impact: Low.** Prescribed burning is not used in established softwood plantations, however, fire may be used in establishment and softwood plantations remain susceptible to bushfires and thus can contribute to particulate and other chemical emissions with significant impacts on human health. VOC emissions are significantly lower for softwoods than hardwoods.
- **Severity of consequences: Low.** Community concern about the health impacts of smoke is high and there is some concern about the contribution of biogenic VOCs to urban ozone but the likelihood of regulatory restrictions is considered to be low.

HARDWOOD PLANTATIONS	**LOW**

- **Degree of impact: Moderate.** As for softwood plantations but VOC emissions are significantly higher for hardwoods than softwoods.
- **Severity of consequences: Low.** As for softwood plantations.

NATIVE FORESTS	**MODERATE**

- **Degree of impact**: **High.** Hazard reduction burning is routinely used, and native forest is susceptible to bushfires and thus can contribute to particulate and other chemical emissions with significant impacts on human health.
- **Severity of consequences**: **Low.** As for softwood plantations.

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[27] http://nepc.gov.au/nepms/ambient-air-quality (accessed 17 November 2020).

Risk mitigation options

The risks associated with particulate emissions from burning could be mitigated by:

- The use of mechanical fuel reduction practices, such as slashing and mulching in plantations. This is an active area of research and as yet there is little evidence to support the fire hazard reduction attributes of these types of practices at present;[28]
- Exploring options for managing controlled burns to optimise reduced health impacts as well as fuel reduction and regeneration outcomes, for example with improved meteorological modelling (Cope et al. 2019, Paton-Walsh et al. 2019);
- Collaboration in public health management, e.g. the use of apps to warn at-risk populations of potential high particulate level events;[29] and
- Improved community consultation to inform the public of the role of fire in regeneration of harvested native forest.

The risks associated with forest biogenic VOCs emissions could be mitigated by:

- Avoiding the establishment of new plantations in areas surrounding major urban areas;
- Selecting lower VOC-emitting species for new plantations; and
- Adaptive management to avoid undertaking activities known to increase biogenic VOC emissions in the short term, such as harvesting (Owen et al. 2013) during high ozone exceedance risk periods.

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[28] https://www.agriculture.gov.au/forestry/national/nbmp (accessed 7 April 2020)

[29] See for example https://airrater.org/ (accessed 26 March 2020).

4. Conclusions and recommendations

This report develops and applies a standardised framework for natural capital risk assessment in forestry, in order to produce the **first systematic, evidence-based assessment of natural capital risks for the Australian forestry sector**, focussing on primary production (forest establishment to harvesting, ending at the mill gate). By providing both a forestry-specific approach and an initial materiality assessment of the Australian forestry sector's natural capital risks, this report aims to simplify, streamline and standardise the process of natural capital risk assessment for individual forest estates within Australia.

Natural capital risk assessment offers a range of benefits to companies, from improved decision-making, to more comprehensive risk management (ACCA, 2019) and the ability to access natural capital financing opportunities (Smith et al. 2020). Having a standardised framework for assessing and reporting on natural capital risk also enables communication of reliable, consistent and comparable information to investors, regulators and other stakeholders, such as certification bodies. With information on natural capital risks, investors and lenders would be able to allocate capital more efficiently to more sustainably managed, lower-risk operators, thus increasing portfolio returns while simultaneously driving environmental benefits. A standardised framework likewise can assist the financial sector with reporting on their own portfolio risk to financial regulators and other stakeholders. Finally, a standardised framework offers an opportunity to streamline natural capital related information requirements across multiple reporting standards.

The report identifies the main dependency and impact risks for the Australian forestry industry (sub-divided into softwood plantations, hardwood plantations, and native forests), and rates the materiality of these risks based on evidence from published literature and expert knowledge. Overall, the assessment found that the materiality of risks associated with natural capital dependencies (natural capital that forestry businesses depend on) were generally moderate to high. By contrast, the materiality of risks associated with impacts (natural capital that forestry businesses impact on) were mostly low to moderate, with softwood and hardwood plantations having similar profiles, slightly different to the profile for native forests.

The most material risks for Australian forestry were associated with water availability, temperature, bushfire, storms and floods, soil quality and pests and diseases (for all sub-sectors), and biodiversity (for native forests). All of these highly material risks arise from natural capital dependencies, apart from biodiversity, which was an impact risk for native forests only, and bushfire and soil quality which were both a highly material dependency risk and a highly material impact risk. In the past, most environmental management attention within primary industries such as forestry has focussed on impacts. Our analysis suggests that greater awareness of the importance of dependencies will be important to achieving more comprehensive risk management in future.

Climate change is an underlying driver of environmental change affecting all of the most highly material dependencies, whilst also potentially exacerbating biodiversity and pests and diseases impacts. Changes in rainfall regimes, temperature regimes and associated changes in fire regimes and the distribution of pests and diseases pose a combination of direct and indirect risks for the industry. The Australian Prudential Regulation Authority (APRA) has already identified climate change as a material issue for the financial sector in Australia, largely reflecting its indirect exposure to climate risks affecting other sectors of the economy (APRA 2019). This report expands on this and identifies the set of natural capital impact and dependency risks that are potentially material for the Australian forest industry and its stakeholders, including the financial sector, governments and regulators.

4.1 Where does risk lie for softwood plantations?

Figure 4-1 summarises our materiality assessment of natural capital risks for the Australian softwood plantation sector. Dependency risks – arising from the dependencies that businesses have on natural capital – are depicted on the right of the figure, and impact risks – arising from the impacts that businesses have on natural capital – are depicted on the left. The length of the bars represents the materiality assessment for each category of natural capital, such that low materiality is represented with a short bar (close to the centre) and high materiality is represented by a long bar (which extends to the edge of the figure).

Highly material dependency risks for softwood plantations are associated with water availability (including mean rainfall and extremes such as drought), temperature (including mean temperature and extremes such as heat waves and frosts), storms and floods (including wind, flood, cyclones, hail and lightning), bushfires, soil quality and pests and diseases. Moderately material dependency risks arise from biodiversity and weeds, while moderately material impact risks are related to water use, bushfires, biodiversity and weeds impacts.

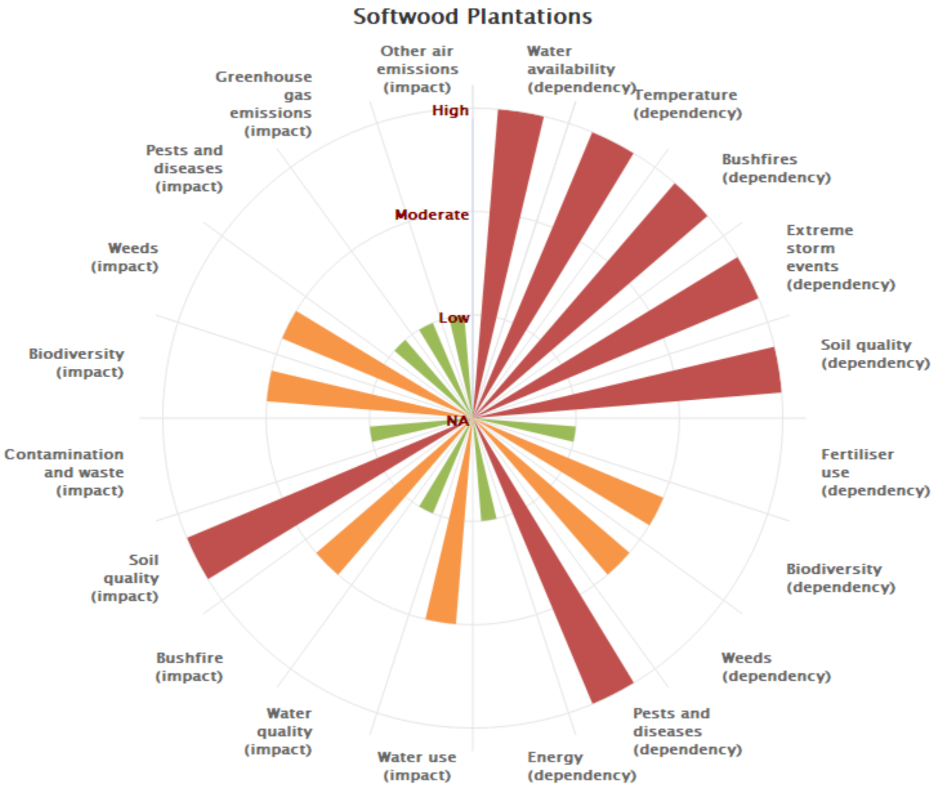

Figure 4-1 Summary of the materiality of dependency and impact risks for softwood plantations.

The size of the bars (and corresponding colour) represent the materiality score associated with each impact and dependency such that a low score is represented with a small bar (close to the centre) and high materiality score is represented by a large bar (which extends to the edge of the figure).

4.2 Where does risk lie for hardwood plantations?

The risk profile for hardwood plantations is similar to that for softwoods. The difference is that the dependency on fertiliser was assessed as moderately material, related to the higher use and reliance on fertilisers in hardwood plantations. Impact risks were also similar, although greenhouse gas emissions impact risk was assessed as moderate materiality in hardwood plantations hardwood production due to the higher proportion of wood that goes towards short-lived fibre products.

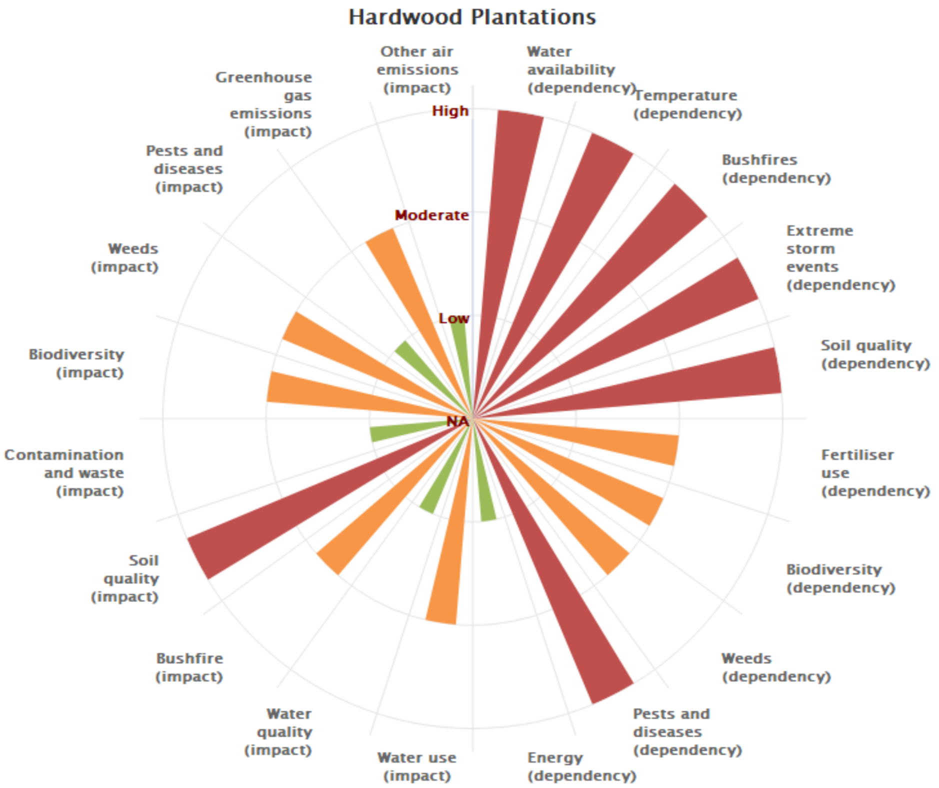

Figure 4-2 Summary of the materiality of impact and dependency risks for hardwood plantations.

The size of the bars (and corresponding colour) represent the materiality score associated with each impact and dependency such that a low score is represented with a small bar (close to the centre) and high materiality score is represented by a large bar (which extends to the edge of the figure).

4.3 Where does risk lie for native forests?

The risk profile for native forests is somewhat different to plantations (Figure 4-3). Highly material dependency risk is again associated with water availability, temperature, bushfires, storms and floods, soil quality, biodiversity and pests and disease.

Unlike plantations, native forestry was associated with highly material impact risks associated with biodiversity and bushfire. The higher biodiversity materiality risk was related to harvesting in native forests, and in particular clearfelling, which can potentially have a significant negative effect on biodiversity, in addition, there is considerable community concern about native forest harvesting. The higher material bushfire materiality risk was related to the more frequent and extensive use of fire in native forests which means that the risks of escape are higher. Native forestry was also associated with moderately material impact risks associated with other air emissions, largely due to the health effects and community concerns regarding smoke.

Native forestry was also assessed as having some lower materiality risks than plantations, for example, for native forestry the impact on water use and weed were assessed as low materiality, and the dependency on fertiliser was rated as not applicable because fertiliser is not used in native forestry.

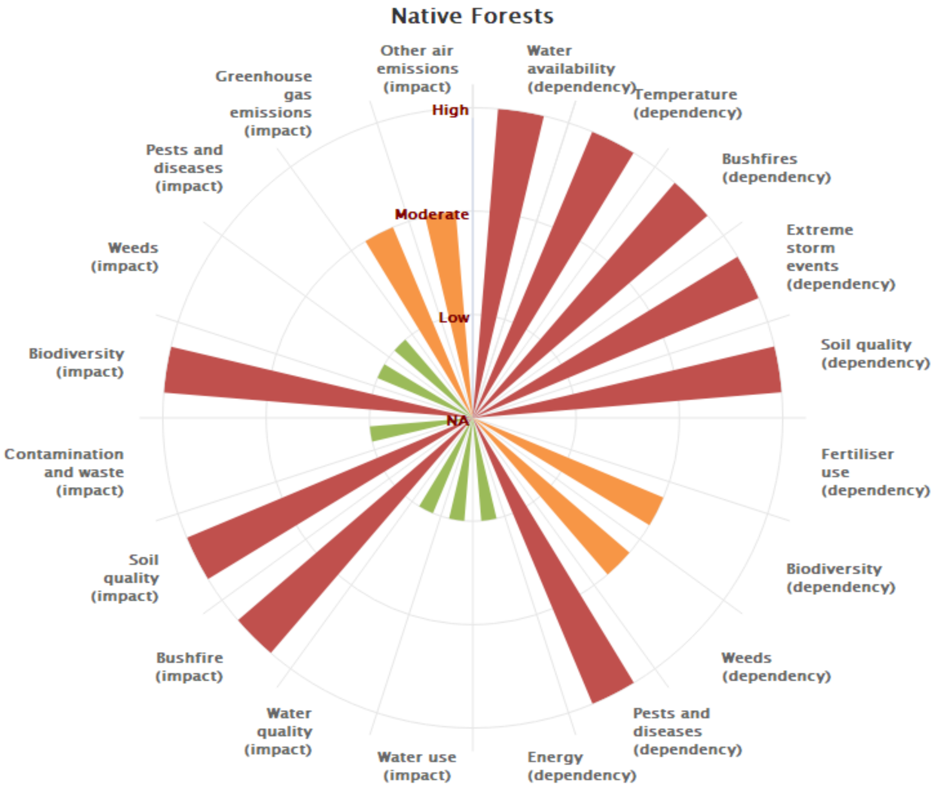

Figure 4-3 Summary of the materiality of impact and dependency risks for native forest.

The size of the bars (and corresponding colour) represent the materiality score associated with each impact and dependency such that a low score is represented with a small bar (close to the centre) and high materiality score is represented by a large bar (which extends to the edge of the figure).

4.4 Recommendations

4.4.1 Company- or estate-level risk assessments and risk management can be targeted and cost-effective

The potential scope of natural capital dependencies and impacts for any industry is vast, with hundreds of different ecosystem services being identified in international classifications (Haines-Young and Potschin 2017). The framework for forestry presented in this report simplifies this to just twenty key risk areas of relevance to Australian forestry, of which only five have been assessed as highly material for each industry sub-sector. This means that forestry companies, investors and other stakeholders can focus their available resources on more cost-effective assessment and management of a small set of highly material risks, which can be gradually expanded over time, if necessary and practicable, to include lower materiality risks.

Nevertheless, it must also be recognised that the materiality assessments presented in this report represent a generic assessment for the whole of the Australian forestry sector, and may not accurately represent the situation at any given company or estate level. Individual companies or estates may be exposed to risks that are not captured by the framework, or which are more or less material than our assessments. By providing a systematic framework and including our evidence and rationale, we hope to facilitate the process of materiality assessments at the company or estate level.

It should also be noted that our materiality assessments assume no mitigation beyond implementation of current standard practices, e.g. compliance with regulatory requirements. Options for further mitigation were identified, and can be used to modify materiality assessments at company or estate level.

4.4.2 Greater awareness of dependency risks is required

In the past, most environmental management attention within primary industries such as forestry, as well as investor/lender risk assessment, has focussed on natural capital impacts. However, our analysis shows that the majority of the most highly material risks for the Australian forestry sector are dependency-related, with the only significant exceptions being bushfire and pests and diseases impact risks for native forests. Dependency risks in general are more difficult to manage than impact risks, and greater awareness is a first step towards taking more targeted action to mitigate and manage these risks.

4.4.3 Focus on climate-related natural capital risks

The Australian Prudential Regulation Authority (APRA) has identified climate change as a material issue for the financial sector in Australia, largely reflecting its indirect exposure, for example through investments, lending and insurance, to climate risks affecting other sectors of the economy (APRA 2019). This report demonstrates that climate risk is material for the Australian forestry industry. Most of the highest materiality natural capital risks across the three forest types are related to dependencies which are threatened by climate change. Changes in rainfall regimes and temperature regimes, storms and floods, and associated changes in fire regimes and the distribution of pests and diseases pose a combination of direct and indirect risks for the industry. The long timeframes involved in growing trees, compared with other crops, mean that the long-term effects of climate change are particularly relevant to the sector. On the other hand, the industry is not a large emitter of GHG emissions, and it plays an important role in maintaining carbon stocks in both forests and harvested wood products.

The Australian Securities and Investments Commission provides guidance on how to disclose climate-related risks as part of company operating and financial reporting.[30] This report contributes to the preparedness of forestry companies, and their investors, to address questions around climate-related risks. It also highlights where climate change adaptation should focus to help to mitigate that risk.

4.4.4 Further research should target priority risks

Our review showed that some risk areas are better understood than others. In some cases, a lack of evidence, or uncertainty in the available evidence, has driven a higher materiality assessment, in order to be conservative. Further research could help to clarify these risks and their materiality. For example, much of the uncertainty was related to localised effects of climate change and how this might drive change in key dependencies, such as rainfall, bushfires and storm events. Another key uncertainty is the species-specific responses to these climate change effects. This relates to both how certain tree species might cope under different climate regimes and the changes to biodiversity and ecosystems and how that might affect risks such as the dependencies on biodiversity, weeds and pests and diseases.

4.4.5 The next step is to identify suitable indicators and data to assess, monitor and report on natural capital risks

In order to accurately quantify risk levels at company or estate level, suitable indicators must be identified that adequately represent the risk in question, and which are feasible to measure: in other words, it must be cost-effectively practicable to obtain either qualitative or quantitative data to populate the indicators. Ideally, such indicators and data sources should be harmonised across the industry and meet the needs of all relevant stakeholders, in order to reduce transaction costs and promote trust in the reliability, consistency and comparability of reported information.

A subsequent report will explore potential indicators and sources of data for assessing, monitoring and reporting natural capital impact and dependency risks.

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[30] https://asic.gov.au/ (accessed 26 March 2020).

References

Abosede, E. E. 2013. Effect of crude oil pollution on some soil physical properties. Journal of Agriculture and Vertinary Science **6**:14-17.

Achat, D. L., C. Deleuze, G. Landmann, N. Pousse, J. Ranger, and L. Augusto. 2015. Quantifying consequences of removing harvesting residues on forest soils and tree growth – A meta-analysis. Forest Ecology and Management **348**:124-141.

Adams, P., C. Beadle, N. Mendham, and P. Smethurst. 2003. The impact of timing and duration of grass control on growth of a young Eucalyptus globulus Labill. plantation. New Forests **26**:147-165.

AFAC, and FFMG. 2015. Overview of Prescribed Burning in Australasia: Report for National Burning Project: Sub-Project 1. Australasian Fire and Emergency Service Authorities Council (AFAC) and Forest Fire Management Group (FFMG).

Allen, C. D., D. D. Breshears, and N. G. McDowell. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere **6**.

Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.-H. Lim, G. Allard, S. W. Running, A. Semerci, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management **259**:660-684.

Allen, J. T., and E. R. Allen. 2016. A review of severe thunderstorms in Australia. Atmospheric Research **178**:347-366.

Allen, J. T., and D. J. Karoly. 2014. A climatology of Australian severe thunderstorm environments 1979–2011: inter-annual variability and ENSO influence. International Journal of Climatology **34**:81-97.

Almeida, A. C., P. J. Smethurst, A. Siggins, R. B. L. Cavalcante, and N. Borges Jr. 2016. Quantifying the effects of Eucalyptus plantations and management on water resources at plot and catchment scales. Hydrological Processes **30**:4687-4703.

Altangerel, K., and C. A. Kull. 2013. The prescribed burning debate in Australia: conflicts and compatibilities. Journal of Environmental Planning and Management **56**:103-120.

Andjic, V., A. J. Carnegie, G. S. Pegg, G. E. S. J. Hardy, A. Maxwell, P. W. Crous, C. Pérez, M. J. Wingfield, and T. I. Burgess. 2019. 23 years of research on Teratosphaeria leaf blight of Eucalyptus. Forest Ecology and Management **443**:19-27.

Ansong, M., and C. Pickering. 2013. Are weeds hitchhiking a ride on your car? A systematic review of seed dispersal on cars. Plos One **8**:e80275-e80275.

APRA. 2019. Climate change: Awareness to action. Australian Prudential Regulation Authority (APRA).

Arnold, G. W., D. E. Steven, and J. R. Weeldenburg. 1989. The use of surrounding farmland by western gray kangaroos living in a remnant of wandoo woodland and their impact on crop production. Wildlife Research **16**:85-93.

Ascui, F., and T. F. Cojoianu. 2019a. Implementing natural capital credit risk assessment in agricultural lending. Business Strategy and the Environment **28**:1234-1249.

Ascui, F., and T. F. Cojoianu. 2019b. Natural Capital Credit Risk Assessment In Agricultural Lending: An Approach Based on the Natural Capital Protocol. Natural Capital Finance Alliance, Oxford.

Ascui, F., and T. F. Cojoianu. 2020. Natural capital credit risk assessment. Pages 121-144 *in* J. Ma, B. Caldecott, and U. Volz, editors. Case Studies of Environmental Risk Analysis Methodologies. Network of Central Banks and Supervisors for Greening the Financial System, Paris.

Aust, W. M., and C. R. Blinn. 2004. Forestry best management practices for timber harvesting and site preparation in the eastern United States: An overview of water quality and productivity research during the past 20 years (1982–2002). Water, Air and Soil Pollution: Focus **4**:5-36.

Australian Bureau of Agricultural and Resource Economics and Sciences. 2018. Australia's State of the Forests Report 2018. Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee, Canberra.

Aydin, Y. M., B. Yaman, H. Koca, H. Altiok, Y. Dumanoglu, M. Kara, A. Bayram, D. Tolunay, M. Odabasi, and T. Elbir. 2014. Comparison of biogenic volatile organic compound emissions from broad leaved and coniferous trees in Turkey. WIT Transactions on Ecology and the Environment **181**:647-658.

Ayres, M. P., and M. J. Lombardero. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Science of the Total Environment **262**:263-286.

Baillie, B. R., and D. G. Neary. 2015. Water quality in New Zealand's planted forests: a review. New Zealand Journal of Forestry Science **45**:7.

Baker, S. C., S. J. Grove, L. Forster, K. J. Bonham, and D. Bashford. 2009. Short-term responses of ground-active beetles to alternative silvicultural systems in the Warra Silvicultural Systems Trial, Tasmania, Australia. Forest Ecology and Management **258**:444-459.

Baker, S. C., T. A. Spies, T. J. Wardlaw, J. Balmer, J. F. Franklin, and G. J. Jordan. 2013. The harvested side of edges: Effect of retained forests on the re-establishment of biodiversity in adjacent harvested areas. Forest Ecology and Management **302**:107-121.

Baker, T. G., J. N. Cameron, P. C. Fagg, and D. Matthews. 1988. Effect of timing and rate of hexazinone application on weed control and early growth of Pinus radiata on two contrasting sites. Australian Forestry **51**:92-97.

Baker, T. P., S. C. Baker, P. J. Dalton, N. M. Fountain-Jones, and G. J. Jordan. 2016. Temporal persistence of edge effects on bryophytes within harvested forests. Forest Ecology and Management **375**:223-229.

Balmer, J. 2016. Floristic response to landscape context in vascular plant communities in Eucalyptus obliqua and Eucalyptus regnans wet forest, southern Tasmania.

Bari, M. A., and J. K. Ruprecht. 2003. Water yield response to land use change in south–west Western Australia. Department of Environment, Salinity and Land Use Impact Series: SLUI 31.

Barker, D. H., B. R. Loveys, J. J. G. Egerton, H. Gorton, W. E. Williams, and M. C. Ball. 2005. CO2 enrichment predisposes foliage of a eucalypt to freezing injury and reduces spring growth. Plant Cell and Environment **28**:1506-1515.

Barron, O., R. Crosbie, S. Charles, W. Dawes, R. Ali, W. Evans, R. Cresswell, D. Pollock, G. Hodgson, and D. Currie. 2011. Climate change impact on groundwater resources in Australia: Summary Report. CSIRO Water for a Healthy Country Flagship, Australia.

Bartlett, A. G. 2012. Fire management strategies for Pinus radiata plantations near urban areas. Australian Forestry **75**:43-53.

Bates, B. C., P. Hope, B. Ryan, I. Smith, and S. Charles. 2008. Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. Climatic Change **89**:339-354.

Battaglia, M. 1993. Seed germination physiology of Eucalyptus delegatensis RT Baker in Tasmania. Australian Journal of Botany **41**:119-136.

Battaglia, M., and J. Bruce. 2017. Direct climate change impacts on growth and drought risk in blue gum (Eucalyptus globulus) plantations in Australia. Australian Forestry **80**:216-227.

Battaglia, M., J. Bruce, C. Brack, and T. Baker. 2009. Climate change and Australia's plantation estate: analysis of vulnerability and preliminary investigation of adaptation options. Report to Forest and Wood Products Australia, Melbourne.

Battaglia, M., M. L. Cherry, C. L. Beadle, P. J. Sands, and A. Hingston. 1998. Prediction of leaf area index in eucalypt plantations: effects of water stress and temperature. Tree Physiology **18**:521-528.

Battaglia, M., and K. J. Williams. 1996. Mixed species stands of eucalypts as ecotones on a water supply gradient. Oecologia **108**:518-528.

Bauweraerts, I., M. Ameye, T. M. Wertin, M. A. McGuire, R. O. Teskey, and K. Steppe. 2014. Water availability is the decisive factor for the growth of two tree species in the occurrence of consecutive heat waves. Agricultural and Forest Meteorology **189**:19-29.

Beaumont, L. J., T. Hartenthaler, M. R. Keatley, and L. E. Chambers. 2015. Shifting time: recent changes to the phenology of Australian species. Climate Research **63**:203-214.

Bell, T., and I. Oliveras. 2006. Perceptions of Prescribed Burning in a Local Forest Community in Victoria, Australia. Environmental management **38**:867-878.

Bellingham, P. J. 2008. Cyclone effects on Australian rain forests: An overview. Austral Ecology **33**:580-584.

Benyon, R. G., S. Theiveyanathan, and T. M. Doody. 2006. Impacts of tree plantations on groundwater in south-eastern Australia. Australian Journal of Botany **54**:181-192.

Blennow, K., M. Andersson, J. Bergh, O. Sallnas, and E. Olofsson. 2010a. Potential climate change impacts on the probability of wind damage in a south Swedish forest. Climatic Change **99**:261-278.

Blennow, K., M. Andersson, O. Sallnas, and E. Olofsson. 2010b. Climate change and the probability of wind damage in two Swedish forests. Forest Ecology and Management **259**:818-830.

Boer, M. M., V. Resco de Dios, and R. A. Bradstock. 2020. Unprecedented burn area of Australian mega forest fires. Nature Climate Change **10**:171-172.

Boesing, A. L., E. Nichols, and J. P. Metzger. 2017. Effects of landscape structure on avian-mediated insect pest control services: a review. Landscape Ecology **32**:931-944.

Booth, T. H. 2013. Eucalypt plantations and climate change. Forest Ecology and Management **301**:28-34.

Booth, T. H., L. M. Broadhurst, E. Pinkard, S. M. Prober, S. K. Dillon, D. Bush, K. Pinyopusarerk, J. C. Doran, M. Ivkovich, and A. G. Young. 2015. Native forests and climate change: Lessons from eucalypts. Forest Ecology and Management **347**:18-29.

Booth, T. H., M. U. F. Kirschbaum, and M. Battaglia. 2010. Forestry.*in* C. Stokes and M. Howden, editors. Adapting Agriculture to Climate Change: Preparing Australian Agriculture, Forestry and Fisheries for the Future. CSIRO Publishing.

Boston, K. 2016. The Potential Effects of Forest Roads on the Environment and Mitigating their Impacts. Current Forestry Reports **2**:215-222.

Boulter, S. 2012. An assessment of the vulnerability of Australian forests to the impacts of climate change: Synthesis: Contribution of Work Package 5 to the Forest Vulnerability Assessment. National Climate Change Adaptation Research Facility, Gold Coast, Australia.

Bowman, D. M. J. S., G. J. Williamson, R. J. Keenan, and L. D. Prior. 2014. A warmer world will reduce tree growth in evergreen broadleaf forests: evidence from Australian temperate and subtropical eucalypt forests. Global Ecology and Biogeography **23**:925-934.

Brockerhoff, E. G., H. Jactel, J. A. Parrotta, and S. F. B. Ferraz. 2013. Role of eucalypt and other planted forests in biodiversity conservation and the provision of biodiversity-related ecosystem services. Forest Ecology and Management **301**:43-50.

Brockerhoff, E. G., H. Jactel, J. A. Parrotta, C. P. Quine, and J. Sayer. 2008. Plantation forests and biodiversity: oxymoron or opportunity? Biodiversity and Conservation **17**:925-951.

Brown, M. J. 1996. Benign neglect and active management in Tasmania's forests: a dynamic balance or ecological collapse? Forest Ecology and Management **85**:279-289.

Buck, T. 2019. Germans devastated by grim future of fairytale forests. Financial Times: 16 August.

Bungey, R. S. 1966. The biology, behaviour and chemical control of Ips grandicollis in pine slash. University of Adelaide.

Burdon, J. J., P. H. Thrall, and L. Ericson. 2006. The current and future dynamics of disease in plant communities. Annual Review of Phytopathology **44**:19-39.

Burrows, N., and L. McCaw. 2013. Prescribed burning in southwestern Australian forests. Frontiers in Ecology and the Environment **11**:e25-e34.

Burton, J., J. Cawson, P. Noske, and G. Sheridan. 2019. Shifting States, Altered Fates: Divergent Fuel Moisture Responses after High Frequency Wildfire in an Obligate Seeder Eucalypt Forest. Forests **10**:436.

Bush, D., C. Harwood, and E. Pinkard. 2018. Species for changing climates - Australian dryland forestry opportunities. Australian Forestry **81**:102-115.

Cai, W., T. Cowan, and M. Raupach. 2009. Positive Indian Ocean Dipole events precondition southeast Australia bushfires. Geophysical Research Letters **36**.

Calder, I. R. 1998. Water use by forests, limits and controls. Tree Physiology **18**:625-631.

Calviño-Cancela, M., and E. J. B. van Etten. 2018. Invasive potential of Eucalyptus globulus and Pinus radiata into native eucalypt forests in Western Australia. Forest Ecology and Management **424**:246-258.

Cambi, M., G. Certini, F. Fabiano, C. Foderi, A. Laschi, and R. Picchio. 2015. Impact of wheeled and tracked tractors on soil physical properties in a mixed conifer stand. iForest-Biogeosciences and Forestry **9**:89.

Cameron, N., T. Wardlaw, T. Venn, A. Carnegie, and S. Lawson. 2018. Costs and benefits of a leaf beetle Integrated Pest Management (IPM) program II. Cost-benefit analysis. Australian Forestry **81**:53-59.

Carlyle, J. C., M. W. Bligh, and E. K. S. Nambiar. 1998. Woody residue management to reduce nitrogen and phosphorus leaching from sandy soil after clear-felling Pinus radiata plantations. Canadian Journal of Forest Research **28**:1222-1232.

Carnegie, A., S. Lawson, N. Cameron, T. Wardlaw, and T. Venn. 2017. Evaluating the costs and benefits of managing new and existing biosecurity threats to Australia's plantation industry. Prepared for the Forest & Wood Products Australia PNC362-1415, Melbourne.

Carnegie, A. J., and P. K. Ades. 2003. Mycosphaerella leaf disease reduces growth of plantation-grown Eucalyptus globulus. Australian Forestry **66**:113-119.

Carnegie, A. J., and R. Bashford. 2012. Sirex woodwasp in Australia: current management strategies, research and emerging issues. Pages 175-201 The Sirex Woodwasp and its Fungal Symbiont:. Springer.

Carnegie, A. J., A. Kathuria, G. S. Pegg, P. Entwistle, M. Nagel, and F. R. Giblin. 2016. Impact of the invasive rust Puccinia psidii (myrtle rust) on native Myrtaceae in natural ecosystems in Australia. Biological Invasions **18**:127-144.

Carnegie, A. J., P. J. Keane, P. K. Ades, and I. W. Smith. 1994. Variation in Susceptibility of Eucalyptus-Globulus Provenances to Mycosphaerella Leaf Disease. Canadian Journal of Forest Research **24**:1751-1757.

Carnegie, A. J., M. Matsuki, D. A. Haugen, B. P. Hurley, R. Ahumada, P. Klasmer, J. Sun, and E. T. Iede. 2006. Predicting the potential distribution of Sirex noctilio (Hymenoptera: Siricidae), a significant exotic pest of Pinus plantations. Annals of Forest Science **63**:119-128.

Carnegie, A. J., and G. S. Pegg. 2018. Lessons from the Incursion of Myrtle Rust in Australia. Annual Review of Phytopathology **56**:457-478.

Carnegie, A. J., T. Venn, S. Lawson, M. Nagel, T. Wardlaw, N. Cameron, and I. Last. 2018. An analysis of pest risk and potential economic impact of pine wilt disease to Pinus plantations in Australia. Australian Forestry **81**:24-36.

Carvalhais, N., M. Forkel, M. Khomik, J. Bellarby, M. Jung, M. Migliavacca, S. Saatchi, M. Santoro, M. Thurner, and U. Weber. 2014. Global covariation of carbon turnover times with climate in terrestrial ecosystems. Nature **514**:213-217.

Cecutti, C., and D. Agius. 2008. Ecotoxicity and biodegradability in soil and aqueous media of lubricants used in forestry applications. Bioresource Technology **99**:8492-8496.

Chen, Y. L., L. H. Kang, N. Malajczuk, and B. Dell. 2006. Selecting ectomycorrhizal fungi for inoculating plantations in south China: effect of Scleroderma on colonization and growth of exotic Eucalyptus globulus, E. urophylla, Pinus elliottii, and P. radiata. Mycorrhiza **16**:251-259.

Clarke, H., A. J. Pitman, J. Kala, C. Carouge, V. Haverd, and J. P. Evans. 2016. An investigation of future fuel load and fire weather in Australia. Climatic Change **139**:607-607.

Clarke, H. G., P. L. Smith, and A. J. Pitman. 2011. Regional signatures of future fire weather over eastern Australia from global climate models. International Journal of Wildland Fire **20**:550-562.

Close, D. C., and C. L. Beadle. 2003. Chilling-dependent photoinhibition, nutrition and growth analysis of Eucalyptus nitens seedlings during establishment. Tree Physiology **23**:217-226.

COAG. 2004. Intergovernmental agreement on a national water initiative.

Cope, M., S. Lee, M. Meyer, F. Reisen, C. Trindade, A. Sullivan, N. Surawski, A. Wain, D. Smith, B. Ebert, C. Weston, L. Volkova, K. Tolhurst, T. Duff, S. Walsh, N. Tapper, S. Harris, C. Rudiger, A. Holmes, M. Kilinc, C. Paton-Walsh, E. A. Guerette, M. Desservettaz, G. Edwards, K. Macsween, and D. Howard. 2019. Smoke emission and transport modelling, research report 102. Department of Environment, Land, Water and Planning (DELWP).

Coppoletta, M., K. E. Merriam, and B. M. Collins. 2016. Post-fire vegetation and fuel development influences fire severity patterns in reburns. Ecological Applications **26**:686-699.

Coutu, P. 2019. Oil Price Volatility: Does it Impact Delivered Log Costs? , Forest2Market.

Cremer, K. 1984a. Nature and impact of damage by wind, hail and snow in Australia's pine plantations. Australian Forestry **47**:28-38.

Cremer, K. W. 1984b. Hail damage in Australian pine plantations I. Nature and extent of damage. Australian Forestry **47**:103-114.

Crosbie, R., I. Jolly, F. Leaney, C. Petheram, and D. Wohling. 2010. Review of Australian Groundwater Recharge Studies. CSIRO: Water for a Healthy Country National Research Flagship.

Crosbie, R. S., J. L. McCallum, G. R. Walker, and F. H. S. Chiew. 2012. Episodic recharge and climate change in the Murray-Darling Basin, Australia. Hydrogeology Journal **20**:245-261.

Crous, K. Y., A. G. Quentin, Y.-S. Lin, B. E. Medlyn, D. G. Williams, C. V. M. Barton, and D. S. Ellsworth. 2013. Photosynthesis of temperate Eucalyptus globulus trees outside their native range has limited adjustment to elevated CO2 and climate warming. Global Change Biology **19**:3790-3807.

CSIRO, and Bureau of Meteorology. 2015. Climate Change in Australia Information for Australia’s Natural Resource Management Regions: Technical Report. CSIRO and Bureau of Meteorology, Australia.

CSIRO, and Bureau of Meteorology. 2018. State of the Climate 2018.

Cunningham, S., and J. Read. 2002. Comparison of temperate and tropical rainforest tree species: photosynthetic responses to growth temperature. Oecologia **133**:112-119.

Cunningham, S. C., J. R. Thomson, R. Mac Nally, J. Read, and P. J. Baker. 2011. Groundwater change forecasts widespread forest dieback across an extensive floodplain system. Freshwater Biology **56**:1494-1508.

Davidson, E. A., and I. A. Janssens. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature **440**:165-173.

Davis, N. E., A. Bennett, D. M. Forsyth, D. M. J. S. Bowman, E. C. Lefroy, S. W. Wood, A. P. Woolnough, P. West, J. O. Hampton, and C. N. Johnson. 2016. A systematic review of the impacts and management of introduced deer (family Cervidae) in Australia. Wildlife Research **43**:515-532.

Desservettaz, M., F. Phillips, T. Naylor, O. Price, S. Samson, J. Kirkwood, and C. Paton-Walsh. 2019. Air quality impacts of smoke from hazard reduction burns and domestic wood heating in western Sydney. Atmosphere **10**:557.

Doctors for the environment Australia. 2017. Bushfires and health in a changing environment: fact sheet.

Donohue, R., M. Roderick, and T. R. McVicar. 2007. On the importance of including vegetation dynamics in Budyko's hydrological model. Hydrology and Earth System Sciences **11**:983-995.

Downes, G., C. Harwood, R. Washusen, N. Ebdon, R. Evans, D. White, and I. Dumbrell. 2014. Wood properties of Eucalyptus globulus at three sites in Western Australia: effects of fertiliser and plantation stocking. Australian Forestry **77**:179-188.

Downes, G. M., J. Bruce, D. M. Drew, M. Battaglia, and E. Pinkard. 2013. Climate effects on wood properties. CSIRO Report for Forest and Wood Products Australia.

Drew, D. M., and J. Bruce. 2013. The effects of varied temperature and rainfall on wod density and stand volume of Pinus radiata. CSIRO Report to Forest and Wood Products Australia.

Drew, D. M., J. Bruce, and G. M. Downes. 2017. Future wood properties in Australian forests: effects of temperature, rainfall and elevated CO2. Australian Forestry **80**:242-254.

Drew, D. M., G. M. Downes, A. P. O'Grady, J. Read, and D. Worledge. 2009. High resolution temporal variation in wood properties in irrigated and non-irrigated Eucalyptus globulus. Annals of Forest Science **66**.

Ducket, T. 1989. Managing Tasmaniaís pampas grass problem: a strategy for control. Tasforests.

Dutkowski, G. W., and B. M. Potts. 2012. Genetic variation in the susceptibility of Eucalyptus globulus to drought damage. Tree Genetics & Genomes **8**:757-773.

Earman, S., and M. Dettinger. 2011. Potential impacts of climate change on groundwater resources–a global review. Journal of Water Climate Change **2**:213-229.

Eburn, M., and G. Cary. 2016. You own the fuel, but who owns the fire?*in* Hazards CRC & AFAC conference, Brisbane, 30 August – 1 September 2016.

Elek, J., G. R. Allen, and M. Matsuki. 2004. Effects of spraying with Dominex and Success on target and non-target species and rate of recolonisation after spraying in Eucalyptus nitens plantations in Tasmania. Technical Report No TR133. Cooperative Research Centre for Sustainable Production Forestry, Australia.

Elek, J., and T. Wardlaw. 2013. Options for managing chrysomelid leaf beetles in Australian eucalypt plantations: reducing the chemical footprint. Agricultural and Forest Entomology **15**:351-365.

Elliot, W. J., D. Page-Dumroese, and P. R. Robichaud. 1998. The Effects of Forest Management on Erosion and Soil Productivity. Page 195 *in* R. Lal, editor. Soil quality and soil erosion. CRC Press.

Elliott, H. J., R. Bashford, A. Greener, and S. G. Candy. 1992. Integrated pest management of the Tasmanian Eucalyptus leaf beetle, Chrysophtharta bimaculata (Olivier)(Coleoptera: Chrysomelidae). Forest Ecology and Management **53**:29-38.

Elliott, H. J., J. E. Hickey, and S. M. Jennings. 2005. Effects of selective logging and regeneration treatments on mortality of retained trees in Tasmanian cool temperate rainforest. Australian Forestry **68**:274-280.

Ellis, T. W., and T. J. Hatton. 2008. Relating leaf area index of natural eucalypt vegetation to climate variables in southern Australia. Agricultural Water Management **95**:743-747.

Ellison, J. C., P. J. Smethurst, B. M. Morrison, D. Keast, A. Almeida, P. Taylor, Q. F. Bai, D. J. Penton, and H. F. Yu. 2019. Real-time river monitoring supports community management of low-flow Cheek for periods. Journal of Hydrology **572**:839-850.

Emmerson, K. M., I. E. Galbally, A. B. Guenther, C. Paton-Walsh, E. A. Guerette, M. E. Cope, M. D. Keywood, S. J. Lawson, S. B. Molloy, E. Dunne, M. Thatcher, T. Karl, and S. D. Maleknia. 2016. Current estimates of biogenic emissions from eucalypts uncertain for southeast Australia. Atmosheric Chemistry and Physics **16**:6997-7011.

England, J., S. Roxburgh, and P. Polglase. 2014. Review of long-term trends in soil carbon stocks under harvested native forests in Australia. Report prepared for Department of the Environment, CSIRO Sustainable Agriculture Flagship, Australia.

England, J. R., B. May, R. J. Raison, and K. I. Paul. 2013. Cradle-to-gate inventory of wood production from Australian softwood plantations and native hardwood forests: Carbon sequestration and greenhouse gas emissions. Forest Ecology and Management **302**:295-307.

Environment and Natural Resources Committee. 2008. Inquiry into the Impact of Public Land Management Practices on Bushfires in Victoria. Victoria.

Eyles, A., D. Worledge, P. Sands, M. L. Ottenschlaeger, S. C. Paterson, D. Mendham, and A. P. O'Grady. 2012. Ecophysiological responses of a young blue gum (Eucalyptus globulus) plantation to weed control. Tree Physiology **32**:1008-1020.

Fedrowitz, K., J. Koricheva, S. C. Baker, D. B. Lindenmayer, B. Palik, R. Rosenvald, W. Beese, J. F. Franklin, J. Kouki, E. Macdonald, C. Messier, A. Sverdrup-Thygeson, and L. Gustafsson. 2014. REVIEW: Can retention forestry help conserve biodiversity? A meta-analysis. Journal of Applied Ecology **51**:1669-1679.

Fernandes, P. M., and H. S. Botelho. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of Wildland Fire **12**:117-128.

Filoso, S., M. O. Bezerra, K. C. B. Weiss, and M. A. Palmer. 2017. Impacts of forest restoration on water yield: A systematic review. Plos One **12**.

Fleming, A., A. P. O’grady, D. Mendham, J. England, P. Mitchell, M. Moroni, and A. Lyons. 2019. Understanding the values behind farmer perceptions of trees on farms to increase adoption of agroforestry in Australia. Agronomy for Sustainable Development **39**:9.

Ford, R. M., and K. J. H. Williams. 2016. How can social acceptability research in Australian forests inform social licence to operate? Forestry: An International Journal of Forest Research **89**:512-524.

Forest Practices Authority. 2015. The Forest Practices Code 2015. Forest Practices Authority, Hobart, Tasmania.

Forestry Commission. 2018. Natural Capital Account 2017/18. Forest Enterprises England.

Forestry Corporation NSW. 2019. Sustainability Report 2018-19. New South Wales.

Forico, and IDEEA Group. 2018. Making Every Hectare Count: Environmental-Economic Accounting for Forico’s Surrey Hills Estate, Tasmania. IDEEA Group, Australia.

Forsyth, A. R., K. A. Bubb, and M. E. Cox. 2006. Runoff, sediment loss and water quality from forest roads in a southeast Queensland coastal plain Pinus plantation. Forest Ecology and Management **221**:194-206.

Fountain-Jones, N. M., G. J. Jordan, T. P. Baker, J. M. Balmer, T. Wardlaw, and S. C. Baker. 2015. Living near the edge: being close to mature forest increases the rate of succession in beetle communities. Ecological Applications **25**:800-811.

FSC Australia. 2018. The FSC National Forest Stewardship Standardof Australia. Forest Stewardship Council: FSC-STD-AUS-01-2018 EN.

Gawith, D., A. Greenaway, O. Samarasinghe, K. Bayne, S. Velarde, and A. Kravchenko. 2020. Socio-ecological mapping generates public understanding of wilding conifer incursion. Biological Invasions **22**:3031-3049.

Global Impact Investing Network. 2018. Roadmap for the Future of Impact Investing: Reshaping Financial Markets. Global Impact Investing Network (GIIN), New York.

Government of South Australia. 2009. Managing the water resource impacts of plantation forests: A Statewide policy framework.

Government of Western Australia: Department of Water. 2009. Plantation forestry and water management guideline. Australian Government: Water for the Future, Western Australia.

Grice, A. C. 2006. The impacts of invasive plant species on the biodiversity of Australian rangelands. The Rangeland Journal **28**:27-35.

Grigal, D. F. 2000. Effects of extensive forest management on soil productivity. Forest Ecology and Management **138**:167-185.

Grimbacher, P., M. Matsuki, N. Collett, J. Elek, and T. Wardlaw. 2011. Are insect herbivores in Eucalyptus globulus/nitens plantations a worsening problem? A multi-region spatiotemporal review of southern Australia. Technical Report 216, Cooperative Research Centre for Forestry, Hobart, Tasmania.

Haines-Young, R., and M. B. Potschin. 2017. Common International Classification ofEcosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure.

Hardaker, J. B., G. Lien, J. R. Anderson, and R. B. M. Huirne. 2015. Coping with Risk in Agriculture: Applied Decision Analysis. 3rd edition. CABI.

Harvey, D. 2007. Accounting for plantation forest groundwater impacts in the lower South East of South Australia. Department of Water, Land and Biodiversity Conservation (Government of South Australia).

Hasson, A. E. A., G. A. Mills, B. Timbal, and K. Walsh. 2008. Assessing the impact of climate change on extreme fire weather in southeast Australia. CAWCR Technical Report No. 007, Melbourne.

Hasson, A. E. A., G. A. Mills, B. Timbal, and K. Walsh. 2009. Assessing the impact of climate change on extreme fire weather events over southeastern Australia. Climate Research **39**:159-172.

He, C., F. Murray, and T. Lyons. 2000. Monoterpene and isoprene emissions from 15 Eucalyptus species in Australia. Atmospheric Environment **34**:645-655.

Hickey, M. B. C., and B. Doran. 2004. A Review of the Efficiency of Buffer Strips for the Maintenance and Enhancement of Riparian Ecosystems. Water Quality Research Journal **39**:311-317.

Hill, G. J. E., A. Barnes, and G. R. Wilson. 1988. The Use of Wheat Crops by Grey Kangaroos, Macropus-Giganteus, in Southern Queensland. Wildlife Research **15**:111-117.

Hill, K. J., A. Santoso, and M. H. England. 2009. Interannual Tasmanian Rainfall Variability Associated with Large-Scale Climate Modes. Journal of Climate **22**:4383-4397.

Hingston, A. B., and S. Grove. 2010. From clearfell coupe to old-growth forest: Succession of bird assemblages in Tasmanian lowland wet eucalypt forests. Forest Ecology and Management **259**:459-468.

Hingston, A. B., G. J. Jordan, T. J. Wardlaw, and S. C. Baker. 2014. Bird assemblages in Tasmanian clearcuts are influenced by the age of eucalypt regeneration but not by distance from mature forest. Global Ecology and Conservation **2**:138-147.

Hobley, E., B. Wilson, A. Wilkie, J. Gray, and T. Koen. 2015. Drivers of soil organic carbon storage and vertical distribution in Eastern Australia. Plant and Soil **390**:111-127.

Hollingsworth, I. D., R. Boardman, and R. W. Fitzpatrick. 1996. A soil-site evaluation index of productivity in intensively managed Pinus radiata (D. Don) plantations in South Australia. Environmental Monitoring and Assessment **39**:531-541.

Horton, B. M., M. Glen, N. J. Davidson, D. Ratkowsky, D. C. Close, T. J. Wardlaw, and C. Mohammed. 2013. Temperate eucalypt forest decline is linked to altered ectomycorrhizal communities mediated by soil chemistry. Forest Ecology and Management **302**:329-337.

Hubau, W., S. L. Lewis, O. L. Phillips, K. Affum-Baffoe, H. Beeckman, A. Cuní-Sanchez, A. K. Daniels, C. E. N. Ewango, S. Fauset, J. M. Mukinzi, D. Sheil, B. Sonké, M. J. P. Sullivan, T. C. H. Sunderland, H. Taedoumg, S. C. Thomas, L. J. T. White, K. A. Abernethy, S. Adu-Bredu, C. A. Amani, T. R. Baker, L. F. Banin, F. Baya, S. K. Begne, A. C. Bennett, F. Benedet, R. Bitariho, Y. E. Bocko, P. Boeckx, P. Boundja, R. J. W. Brienen, T. Brncic, E. Chezeaux, G. B. Chuyong, C. J. Clark, M. Collins, J. A. Comiskey, D. A. Coomes, G. C. Dargie, T. de Haulleville, M. N. D. Kamdem, J.-L. Doucet, A. Esquivel-Muelbert, T. R. Feldpausch, A. Fofanah, E. G. Foli, M. Gilpin, E. Gloor, C. Gonmadje, S. Gourlet-Fleury, J. S. Hall, A. C. Hamilton, D. J. Harris, T. B. Hart, M. B. N. Hockemba, A. Hladik, S. A. Ifo, K. J. Jeffery, T. Jucker, E. K. Yakusu, E. Kearsley, D. Kenfack, A. Koch, M. E. Leal, A. Levesley, J. A. Lindsell, J. Lisingo, G. Lopez-Gonzalez, J. C. Lovett, J.-R. Makana, Y. Malhi, A. R. Marshall, J. Martin, E. H. Martin, F. M. Mbayu, V. P. Medjibe, V. Mihindou, E. T. A. Mitchard, S. Moore, P. K. T. Munishi, N. N. Bengone, L. Ojo, F. E. Ondo, K. S. H. Peh, G. C. Pickavance, A. D. Poulsen, J. R. Poulsen, L. Qie, J. Reitsma, F. Rovero, M. D.

Swaine, J. Talbot, J. Taplin, D. M. Taylor, D. W. Thomas, B. Toirambe, J. T. Mukendi, D. Tuagben, P. M. Umunay, G. M. F. van der Heijden, H. Verbeeck, J. Vleminckx, S. Willcock, H. Wöll, J. T. Woods, and L. Zemagho. 2020. Asynchronous carbon sink saturation in African and Amazonian tropical forests. Nature **579**:80-87.

Hughes, L., E. M. Cawsey, and M. Westoby. 1996. Climatic range sizes of Eucalyptus species in relation to future climate change. Global Ecology and Biogeography Letters **5**:23-29.

Hunter Jr, M. L. 1990. Wildlife, forests, and forestry. Principles of managing forests for biological diversity. Prentice Hall.

Hyvönen, R., G. I. Ågren, S. Linder, T. Persson, M. F. Cotrufo, A. Ekblad, M. Freeman, A. Grelle, I. A. Janssens, P. G. Jarvis, S. Kellomäki, A. Lindroth, D. Loustau, T. Lundmark, R. J. Norby, R. Oren, K. Pilegaard, M. G. Ryan, B. D. Sigurdsson, M. Strömgren, M. van Oijen, and G. Wallin. 2007. The likely impact of elevated [CO2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. New Phytologist **173**:463-480.

IFA. 2019. Submission to the AFAC Review into the 2018/19 Tasmanian Bushfires. Institute of Foresters of Australia.

IFA. 2020. Bushfire recovery harvesting operations. The Institute of Foresters of Australia/Australian Forest Growers.

Iinuma, Y., M. Keywood, and H. Herrmann. 2016. Characterization of primary and secondary organic aerosols in Melbourne airshed: The influence of biogenic emissions, wood smoke and bushfires. Atmospheric Environment **130**:54-63.

Independent Pricing and Regulatory Tribunal. 2017. Review of Forestry Corporation of NSW's native timber harvesting and haulage costs. Independent Pricing and Regulatory Tribunal (IPART), New South Wales.

IPCC. 2018. Global Warming of 1.5 ºC: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Ishaq, L., P. A. Barber, G. E. S. J. Hardy, M. Calver, and B. Dell. 2013. Seedling mycorrhizal type and soil chemistry are related to canopy condition of Eucalyptus gomphocephala. Mycorrhiza **23**:359-371.

Jandl, R., M. Lindner, L. Vesterdal, B. Bauwens, R. Baritz, F. Hagedorn, D. W. Johnson, K. Minkkinen, and K. A. Byrne. 2007. How strongly can forest management influence soil carbon sequestration? Geoderma **137**:253-268.

Johnston, F., I. Hanigan, S. Henderson, G. Morgan, and D. Bowman. 2011. Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994–2007. Environmental research **111**:811-816.

Johnston, F. H., S. B. Henderson, Y. Chen, J. T. Randerson, M. Marlier, R. S. DeFries, P. Kinney, D. M. J. S. Bowman, and M. Brauer. 2012. Estimated global mortality attributable to smoke from landscape fires. Environmental health perspectives **120**:695-701.

Kanowski, J., C. P. Catterall, and G. W. Wardell-Johnson. 2005. Consequences of broadscale timber plantations for biodiversity in cleared rainforest landscapes of tropical and subtropical Australia. Forest Ecology and Management **208**:359-372.

Kath, J., K. Reardon-Smith, A. Le Brocque, F. Dyer, E. Dafny, L. Fritz, and M. Batterham. 2014. Groundwater decline and tree change in floodplain landscapes: identifying non-linear threshold responses in canopy condition. Global Ecology Conservation **2**:148-160.

Keith, H., D. B. Lindenmayer, B. G. Mackey, D. Blair, L. Carter, L. McBurney, S. Okada, and T. Konishi-Nagano. 2014. Accounting for biomass carbon stock change due to wildfire in temperate forest landscapes in Australia. Plos One **9**:e107126.

Keith, H., E. van Gorsel, K. L. Jacobsen, and H. A. Cleugh. 2012. Dynamics of carbon exchange in a Eucalyptus forest in response to interacting disturbance factors. Agricultural and Forest Meteorology **153**:67-81.

Keywood, M., M. Cope, C. P. M. Meyer, Y. Iinuma, and K. Emmerson. 2015. When smoke comes to town: The impact of biomass burning smoke on air quality. Atmospheric Environment **121**:13-21.

Keywood, M. D., K. M. Emmerson, and M. F. Hibberd. 2016. Ambient air quality: National air quality standards. Australia state of the environment 2016. Australian Government Department of the Environment and Energy, Canberra.

Kiley, H. M., G. B. Ainsworth, W. F. D. van Dongen, and M. A. Weston. 2017. Variation in public perceptions and attitudes towards terrestrial ecosystems. Science of the Total Environment **590**:440-451.

Kimber, W., R. Glatz, G. Caon, and D. Roocke. 2010. Diaeretus essigellae Starý and Zuparko (Hymenoptera: Braconidae: Aphidiini), a biological control for Monterey pine aphid, Essigella californica (Essig) (Hemiptera: Aphididae: Cinarini): host-specificity testing and historical context. Australian Journal of Entomology **49**:377-387.

Kirschbaum, M. U. F. 2000. Forest growth and species distribution in a changing climate. Tree Physiology **20**:309-322.

Kirschbaum, M. U. F. 2006. The temperature dependence of organic-matter decomposition—still a topic of debate. Soil Biology Biochemistry **38**:2510-2518.

Kirschbaum, M. U. F., M. S. Watt, A. Tait, and A.-G. E. Ausseil. 2012. Future wood productivity of Pinus radiata in New Zealand under expected climatic changes. Global Change Biology **18**:1342-1356.

Klamerus-Iwan, A., E. Blonska, J. Lasota, A. Kalandyk, and P. Waligorski. 2015. Influence of Oil Contamination on Physical and Biological Properties of Forest Soil After Chainsaw Use. Water Air and Soil Pollution **226**:9.

Kløve, B., P. Ala-Aho, G. Bertrand, J. J. Gurdak, H. Kupfersberger, J. Kværner, T. Muotka, H. Mykrä, E. Preda, P. Rossi, C. B. Uvo, E. Velasco, and M. Pulido-Velazquez. 2014. Climate change impacts on groundwater and dependent ecosystems. Journal of Hydrology **518**:250-266.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi. 2010. Tropical cyclones and climate change. Nature Geoscience **3**:157-163.

Koch, A. J., A. Chuter, and S. A. Munks. 2012. A review of forestry impacts on biodiversity and the effectiveness of ‘off-reserve’ management actions in areas covered by the Tasmanian forest practices system. Forest Practices Authority, Hobart.

Kozlowski, T. T. 1999. Soil Compaction and Growth of Woody Plants. Scandinavian Journal of Forest Research **14**:596-619.

Krishna, M. P., and M. Mohan. 2017. Litter decomposition in forest ecosystems: a review. Energy, Ecology and Environment **2**:236-249.

Kriticos, D. J., N. D. Crossman, N. Ota, and J. K. Scott. 2010. Climate change and invasive plants in South Australia. Report for the South Australian Department of Water, Land and Biodiversity Conservation. CSIRO Climate Adaptation Flagship., Canberra, Australia.

Kriticos, D. J., M. S. Watt, K. J. B. Potter, L. K. Manning, N. S. Alexander, and N. Tallent-Halsell. 2011. Managing invasive weeds under climate change: considering the current and potential future distribution of Buddleja davidii. Weed Research **51**:85-96.

Lane, P. N. J., and G. J. Sheridan. 2002. Impact of an unsealed forest road stream crossing: water quality and sediment sources. Hydrological Processes **16**:2599-2612.

Latham, A. D. M., M. C. Latham, G. L. Norbury, D. M. Forsyth, and B. Warburton. 2020. A review of the damage caused by invasive wild mammalian herbivores to primary production in New Zealand. New Zealand Journal of Zoology **47**:20-52.

Lawson, S. A., A. J. Carnegie, N. Cameron, T. Wardlaw, and T. J. Venn. 2018. Risk of exotic pests to the Australian forest industry. Australian Forestry **81**:3-13.

Lefort, P., and S. Grove. 2009. Early responses of birds to clearfelling and its alternatives in lowland wet eucalypt forest in Tasmania, Australia. Forest Ecology and Management **258**:460-471.

Lehmann, J., and M. Kleber. 2015. The contentious nature of soil organic matter. Nature **528**:60-68.

Lindenmayer, D. B., D. R. Foster, J. F. Franklin, M. L. Hunter, R. F. Noss, F. A. Schmiegelow, and D. Perry. 2004. Salvage Harvesting Policies After Natural Disturbance. Science **303**:1303.

Little, K. M., C. A. Rolando, and C. D. Morris. 2007. An integrated analysis of 33 Eucalyptus trials linking the onset of competition-induced tree growth suppression with management, physiographic and climatic factors. Annals of Forest Science **64**:585-591.

Loch, A. D., and R. B. Floyd. 2001. Insect pests of Tasmanian blue gum, Eucalyptus globulus globulus, in south-western Australia: History, current perspectives and future prospects. Austral Ecology **26**:458-466.

Loch, A. D., and M. Matsuki. 2010. Effects of defoliation by Eucalyptus weevil, Gonipterus scutellatus, and chrysomelid beetles on growth of Eucalyptus globulus in southwestern Australia. Forest Ecology and Management **260**:1324-1332.

MacHunter, J., W. Wright, R. Loyn, and P. Rayment. 2006. Bird declines over 22 years in forest remnants in southeastern Australia: Evidence of faunal relaxation? Canadian Journal of Forest Research **36**:2756-2768.

Magierowski, R. H., P. E. Davies, S. M. Read, and N. Horrigan. 2012. Impacts of land use on the structure of river macroinvertebrate communities across Tasmania, Australia: spatial scales and thresholds. Marine and Freshwater Research **63**:762-776.

Marcar, N. E., D. F. Crawford, A. Saunders, A. C. Matheson, and R. A. Arnold. 2002. Genetic variation among and within provenances and families of Eucalyptus grandis W. Hill and E. globulus Labill. subsp. globulus seedlings in response to salinity and waterlogging. Forest Ecology and Management **162**:231-249.

Mariani, M., M. S. Fletcher, A. Holz, and P. Nyman. 2016. ENSO controls interannual fire activity in southeast Australia. Geophysical Research Letters **43**:10891-10900.

Matthews, S., A. L. Sullivan, P. Watson, and R. J. Williams. 2012. Climate change, fuel and fire behaviour in a eucalypt forest. Global Change Biology **18**:3212-3223.

Matusick, G., K. X. Ruthrof, N. C. Brouwers, B. Dell, and G. S. Hardy. 2013. Sudden forest canopy collapse corresponding with extreme drought and heat in a mediterranean-type eucalypt forest in southwestern Australia. European Journal of Forest Research **132**:497-510.

Matzrafi, M. 2019. Climate change exacerbates pest damage through reduced pesticide efficacy. Pest Management Science **75**:9-13.

Matzrafi, M., B. Seiwert, T. Reemtsma, B. Rubin, and Z. Peleg. 2016. Climate change increases the risk of herbicide-resistant weeds due to enhanced detoxification. Planta **244**:1217-1227.

May, B., J. R. England, R. J. Raison, and K. I. Paul. 2012. Cradle-to-gate inventory of wood production from Australian softwood plantations and native hardwood forests: Embodied energy, water use and other inputs. Forest Ecology and Management **264**:37-50.

May, B., P. Smethurst, C. Carlyle, D. Mendham, J. Bruce, and C. Baillie. 2009. Review of fertiliser use in Australian forestry. Forest & Wood Products Australia: PRC072-0708.

May, B. M. 2004. Assessment of the causality of Essigella-ascribed defoliation of mid-rotation radiata pine and its national impact in terms of cost of lost wood production. Forest and Wood Products Research and Development Corporation, Melbourne, Victoria.

May, B. M., and J. C. Carlyle. 2003. Effect of defoliation associated with Essigella californica on growth of mid-rotation Pinus radiata. Forest Ecology and Management **183**:297-312.

McCaw, W. L. 2013. Managing forest fuels using prescribed fire – A perspective from southern Australia. Forest Ecology and Management **294**:217-224.

McFarlane, R. A., A. C. Sleigh, and A. J. McMichael. 2013. Land-use change and emerging infectious disease on an island continent. International journal of environmental research and public health **10**:2699-2719.

McVicar, T. R., M. L. Roderick, R. J. Donohue, L. T. Li, T. G. Van Niel, A. Thomas, J. Grieser, D. Jhajharia, Y. Himri, N. M. Mahowald, A. V. Mescherskaya, A. C. Kruger, S. Rehman, and Y. Dinpashoh. 2012. Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. Journal of Hydrology **416**:182-205.

McVicar, T. R., T. G. Van Niel, L. T. Li, M. L. Roderick, D. P. Rayner, L. Ricciardulli, and R. J. Donohue. 2008. Wind speed climatology and trends for Australia, 1975-2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. Geophysical Research Letters **35**.

Mead, D. J. 2013. Sustainable management of Pinus radiata plantations. FAO, Rome.

Medlyn, B. E., M. Zeppel, N. C. Brouwers, K. Howard, E. O’Gara, G. Hardy, T. Lyons, L. Li, and B. Evans. 2011. Biophysical impacts of climate change on Australia's forests. Contribution of Work Package 2 to the Forest Vulnerability Assessment. National Climate Change Adaptation Research Facility, Gold Coast, Australia.

Mendham, D., D. A. White, M. Battaglia, J. Kinal, S. Walker, S. Rance, J. F. McGrath, and S. Abou Arra. 2007. Managing the trade-off between productivity and risk in the bluegum plantations of south-western Australia. CSIRO, Canberra.

Mendham, D. S., D. A. White, M. Battaglia, J. F. McGrath, T. M. Short, G. N. Ogden, and J. Kinal. 2011. Soil water depletion and replenishment during first- and early second-rotation Eucalyptus globulus plantations with deep soil profiles. Agricultural and Forest Meteorology **151**:1568-1579.

Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington.

Mitchell, P. J., A. P. O'Grady, K. R. Hayes, and E. A. Pinkard. 2014. Exposure of trees to drought-induced die- off is defined by a common climatic threshold across different vegetation types. Ecology and Evolution **4**:1088-1101.

Moore, J. R., and M. S. Watt. 2015. Modelling the influence of predicted future climate change on the risk of wind damage within New Zealand's planted forests. Global Change Biology **21**:3021-3035.

Mummery, D., and M. Battaglia. 2004. Significance of rainfall distribution in predicting eucalypt plantation growth, management options, and risk assessment using the process-based model CABALA. Forest Ecology and Management **193**:283-296.

Munks, S. A., A. E. Chuter, and A. J. Koch. 2020. ‘Off-reserve’management in practice: Contributing to conservation of biodiversity over 30 years of Tasmania’s forest practices system. Forest Ecology and Management **465**:117941.

Myers, B. J., S. Theiveyanathan, N. D. OBrien, and W. J. Bond. 1996. Growth and water use of Eucalyptus grandis and Pinus radiata plantations irrigated with effluent. Tree Physiology **16**:211-219.

Nahrung, H. F., and A. J. Carnegie. 2020. Non-native Forest Insects and Pathogens in Australia: Establishment, Spread, and Impact. Frontiers in Forests and Global Change **3**:37.

Natural Capital Coalition. 2016. Natural Capital Protocol. Natural Capital Coalition, London.

Natural Capital Coalition. 2018. Natural Capital Protocol – Forest Products Sector Guide. Natural Capital Coalition, London.

Natural Capital Declaration. 2012. The Natural Capital Declaration. Natural Capital Declaration, Oxford.

NCFA, and PwC. 2018. Integrating Natural Capital in Risk Assessments: A Step by Step Guide for Banks. Natural Capital Finance Alliance and PricewaterhouseCoopers, Oxford, UK.

NCFA, and UN Environment World Conservation Monitoring Centre. 2018. Exploring natural capital opportunities, risks and exposure: A practical guide for financial institutions. Natural Capital Finance Alliance and UN Environment World Conservation Monitoring Centre.

Neale, D. B., and A. Kremer. 2011. Forest tree genomics: growing resources and applications. Nature Reviews Genetics **12**:111-122.

Neary, D. G., P. B. Bush, and J. L. Michael. 1993. Fate, dissipation and environmental effects of pesticides in southern forests: A review of a decade of research progress. Environmental Toxicology and Chemistry **12**:411-428.

Neilson, W. A. 1990. Plantation handbook. Forestry Commission of Tasmania, Hobart.

Nguyen Duc, H., L. T. C. Chang, T. Trieu, D. Salter, and Y. Scorgie. 2018. Source Contributions to Ozone Formation in the New South Wales Greater Metropolitan Region, Australia. Atmosphere **9**:443.

Norbury, D. C., and G. L. Norbury. 1996. Short-term effects of rabbit grazing on a degraded short-tussock grassland in Central Otago. New Zealand Journal of Ecology:285-288.

Norsworthy, J. K., S. M. Ward, D. R. Shaw, R. S. Llewellyn, R. L. Nichols, T. M. Webster, K. W. Bradley, G. Frisvold, S. B. Powles, N. R. Burgos, W. W. Witt, and M. Barrett. 2012. Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations. Weed Science **60**:31-62.

O'Connell, A. M. 1997. Decomposition of slash residues in thinned regrowth eucalpt forest in Western Australia. Journal of Applied Ecology:111-122.

O'Reilly-Wapstra, J. M., B. M. Potts, C. McArthur, and N. W. Davies. 2005. Effects of nutrient variability on the genetic-based resistance of Eucalyptus globulus to a mammalian herbivore and on plant defensive chemistry. Oecologia **142**:597-605.

O'Sullivan, O. S., M. A. Heskel, P. B. Reich, M. G. Tjoelker, L. K. Weerasinghe, A. Penillard, L. L. Zhu, J. J. G. Egerton, K. J. Bloomfield, D. Creek, N. H. A. Bahar, K. L. Griffin, V. Hurry, P. Meir, M. H. Turnbull, and O. K. Atkin. 2017. Thermal limits of leaf metabolism across biomes. Global Change Biology **23**:209-223.

O'Hehir, J. F., and E. K. S. Nambiar. 2010. Productivity of three successive rotations of P. radiata plantations in South Australia over a century. Forest Ecology and Management **259**:1857-1869.

Old, K. M., and C. Stone. 2005. Vulnerability of Australian forest carbon sinks to pests and pathogens in a changing climate. report to the Australian Greenhouse Office, Canberra.

Ooi, M. K. J. 2012. Seed bank persistence and climate change. Seed Science Research **22**:S53-S60.

Ortega, U., M. Duñabeitia, S. Menendez, C. Gonzalez-Murua, and J. Majada. 2004. Effectiveness of mycorrhizal inoculation in the nursery on growth and water relations of Pinus radiata in different water regimes. Tree Physiology **24**:65-73.

Owen, S. M., C. N. Hewitt, and C. S. Rowland. 2013. Scaling emissions from agroforestry plantations and urban habitats. Pages 415-450 Biology, controls and models of tree volatile organic compound emissions. Springer.

Paton-Walsh, C., P. Rayner, J. Simmons, S. L. Fiddes, R. Schofield, H. Bridgman, S. Beaupark, R. Broome, S. D. Chambers, and L. T.-C. Chang. 2019. A Clean Air Plan for Sydney: An Overview of the Special Issue on Air Quality in New South Wales. Atmosphere **10**:774.

Perkins-Kirkpatrick, S. E., C. J. White, L. V. Alexander, D. Argüeso, G. Boschat, T. Cowan, J. P. Evans, M. Ekström, E. C. J. Oliver, A. Phatak, and A. Purich. 2016. Natural hazards in Australia: heatwaves. Climatic Change **139**:101-114.

Peters, G. M., S. G. Wiedemann, H. V. Rowley, and R. W. Tucker. 2010. Accounting for water use in Australian red meat production. The International Journal of Life Cycle Assessment **15**:311-320.

Pinkard, E., M. Battaglia, J. Bruce, S. Matthews, A. N. Callister, S. Hetherington, I. Last, S. Mathieson, C. Mitchell, C. Mohammed, R. Musk, I. Ravenwood, J. Rombouts, C. Stone, and T. Wardlaw. 2015. A history of forestry management responses to climatic variability and their current relevance for developing climate change adaptation strategies. Forestry **88**:155-171.

Pinkard, E., and J. Bruce. 2011. Climate change and South Australia's plantations: impacts, risks and options for adaptation. CSIRO, Hobart.

Pinkard, E., J. Bruce, M. Battaglia, S. Matthews, D. M. Drew, and G. M. Downes. 2014a. Climate change and Australia's plantations. Forest & Wood Products Australia, Melbourne.

Pinkard, E., J. Bruce, M. Battaglia, S. Matthews, D. M. Drew, G. M. Downes, D. Crawford, and M. Ottenschlaeger. 2014b. Adaptation strategies to manage risk in Australia's plantations. Forest & Wood Products Australia: PNC228-1011, Melbourne.

Pinkard, E., A. Herr, C. Mohammed, M. Glen, T. Wardlaw, and S. Grove. 2009. Predicting NPP of temperate forest systems: uncertainty associated with climate change and pest attack. Client Report No. 167, CSIRO, Australia.

Pinkard, E., T. Wardlaw, D. Kriticos, K. Ireland, and J. Bruce. 2017. Climate change and pest risk in temperate eucalypt and radiata pine plantations: a review. Australian Forestry **80**:228-241.

Polglase, P., and R. G. Benyon. 2009. The impacts of plantations and native forests on water security: Review and scientific assessment of regional issues and research needs. Forest & Wood Products Australia.

Potts, B. M., R. C. Barbour, A. B. Hingston, and R. E. Vaillancourt. 2003. Genetic pollution of native eucalypt gene pools-identifying the risks. Australian Journal of Botany **51**:1-25.

Potts, B. M., M. H. McGowen, D. R. Williams, S. Suitor, T. H. Jones, P. L. Gore, and R. E. Vaillancourt. 2008. Advances in reproductive biology and seed production systems of Eucalyptus: the case of Eucalyptus globulus. Southern Forests: a Journal of Forest Science **70**:145-154.

Power, S., F. Delage, C. Chung, G. Kociuba, and K. Keay. 2013. Robust twenty-first-century projections of El Nino and related precipitation variability. Nature **502**:541-+.

Prosser, I. P., and G. R. Walker. 2009. A review of plantations as a water intercepting land use in South Australia. CSIRO: Water for a Healthy Country National Research Flagship.

Prosser, I. P., and L. Williams. 1998. The effect of wildfire on runoff and erosion in native Eucalyptus forest. Hydrological Processes **12**:251-265.

PwC. 2015. Valuing corporate environmental impacts: PwC methodology document. PricewaterhouseCoopers.

Raison, R. J., and P. K. Khanna. 2011. Possible Impacts of Climate Change on Forest Soil Health. Pages 257-285 *in* B. P. Singh, A. L. Cowie, and K. Y. Chan, editors. Soil Health and Climate Change. Springer Berlin Heidelberg, Berlin, Heidelberg.

Rawal, D. S., S. Kasel, M. R. Keatley, and C. R. Nitschke. 2015a. Climatic and photoperiodic effects on flowering phenology of select eucalypts from south-eastern Australia. Agricultural and Forest Meteorology **214**:231-242.

Rawal, D. S., S. Kasel, M. R. Keatley, and C. R. Nitschke. 2015b. Herbarium records identify sensitivity of flowering phenology of eucalypts to climate: Implications for species response to climate change. Austral Ecology **40**:117-125.

Raymond, C. A., and A. Muneri. 2000. Effect of fertilizer on wood properties of Eucalyptus globulus. Canadian Journal of Forest Research **30**:136-144.

Reisen, F., and S. K. Brown. 2006. Implications for community health from exposure to bushfire air toxics. Environmental Chemistry **3**:235-243.

Reyer, C. P. O., S. Bathgate, K. Blennow, J. G. Borges, H. Bugmann, S. Delzon, S. P. Faias, J. Garcia-Gonzalo, B. Gardiner, J. R. Gonzalez-Olabarria, C. Gracia, J. G. Hernandez, S. Kellomaki, K. Kramer, M. J. Lexer, M. Lindner, E. van der Maaten, M. Maroschek, B. Muys, B. Nicoll, M. Palahi, J. H. N. Palma, J. A. Paulo, H. Peltola, T. Pukkala, W. Rammer, D. Ray, S. Sabate, M. J. Schelhaas, R. Seidl, C. Temperli, M. Tome, R. Yousefpour, N. E. Zimmermann, and M. Hanewinkel. 2017. Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? Environmental Research Letters **12**.

Romanyà, J., and V. R. Vallejo. 2004. Productivity of Pinus radiata plantations in Spain in response to climate and soil. Forest Ecology and Management **195**:177-189.

RSPB. 2017. Accounting for Nature: A Natural Capital Account of the RSPB's estate in England.

Ruthrof, K. X., J. B. Fontaine, G. Matusick, D. D. Breshears, D. J. Law, S. Powell, and G. Hardy. 2016. How drought-induced forest die-off alters microclimate and increases fuel loadings and fire potentials. International Journal of Wildland Fire **25**:819-830.

Schelhaas, M.-J., G.-J. Nabuurs, and A. Schuck. 2003. Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biology **9**:1620-1633.

Scott, J. K., K. L. Batchelor, N. Ota, and P. B. Yeoh. 2008. Modelling climate change impacts on sleeper and alert weeds. CSIRO, Wembley, Australia.

Scott, J. K., H. Murphy, D. J. Kriticos, B. L. Webber, N. Ota, and B. Loechel. 2014. Weeds and climate change: supporting weed management adaptation. CSIRO, Australia.

Scott, R. E., M. G. Neyland, D. J. McElwee, and S. C. Baker. 2012. Burning outcomes following aggregated retention harvesting in old-growth wet eucalypt forests. Forest Ecology and Management **276**:165-173.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science **319**:1238-1240.

Seaton, S., G. Matusick, K. X. Ruthrof, and G. E. S. J. Hardy. 2015. Outbreak of Phoracantha semipunctata in response to severe drought in a Mediterranean Eucalyptus forest. Forests **6**:3868-3881.

Seidl, R., D. Thom, M. Kautz, D. Martin-Benito, M. Peltoniemi, G. Vacchiano, J. Wild, D. Ascoli, M. Petr, J. Honkaniemi, M. J. Lexer, V. Trotsiuk, P. Mairota, M. Svoboda, M. Fabrika, T. A. Nagel, and C. P. O. Reyer. 2017. Forest disturbances under climate change. Nature Climate Change **7**:395-402.

Shammas, K., A. M. O'Connell, T. S. Grove, R. McMurtrie, P. Damon, and S. J. Rance. 2003. Contribution of decomposing harvest residues to nutrient cycling in a second rotation Eucalyptus globulus plantation in south-western Australia. Biology and Fertility of Soils **38**:228-235.

Sharples, J. J., G. J. Cary, P. Fox-Hughes, S. Mooney, J. P. Evans, M. S. Fletcher, M. Fromm, P. F. Grierson, R. Mcrae, and P. Baker. 2016. Natural hazards in Australia: extreme bushfire. Climatic Change **139**:85-99.

Sharples, J. J., G. A. Mills, R. H. McRae, and R. O. Weber. 2010. Foehn-like winds and elevated fire danger conditions in southeastern Australia. Journal of Applied Meteorology and Climatology **49**:1067-1095.

Shearer, B. L., and I. W. Smith. 2000. Diseases of eucalypts caused by soilborne species of Phytophthora and Pythium. Pages 259–291 *in* P. J. Keane, G. A. Kile, F. D. Podger, and B. N. Brown, editors. Diseases and pathogens of eucalypts. CSIRO Publishing: Melbourne.

Simioni, G., P. Ritson, J. McGrath, M. U. F. Kirschbaum, B. Copeland, and I. Dumbrell. 2008. Predicting wood production and net ecosystem carbon exchange of Pinus radiata plantations in south-western Australia: Application of a process-based model. Forest Ecology and Management **255**:901-912.

Singh, S., D. Cunningham, J. Davidson, D. Bush, and S. Read. 2013. Status of Australia’s forest genetic resources. Australian Bureau of Agricultural and Resource Economics and Sciences ABARES Research report 13.3, Canberra.

Skiadaresis, G., J. A. Schwarz, and J. Bauhus. 2019. Groundwater Extraction in Floodplain Forests Reduces Radial Growth and Increases Summer Drought Sensitivity of Pedunculate Oak Trees (Quercus robur L.). Frontiers in Forests and Global Change **2**.

Smethurst, P. J., and E. K. S. Nambiar. 1990a. Distribution of carbon and nutrients and fluxes of mineral nitrogen after clear-felling a Pinus radiata plantation. Canadian Journal of Forest Research **20**:1490-1497.

Smethurst, P. J., and E. K. S. Nambiar. 1990b. Effects of slash and litter management on fluxes of nitrogen and tree growth in a young Pinusradiata plantation. Canadian Journal of Forest Research **20**:1498-1507.

Smith, A. H., T. J. Wardlaw, E. A. Pinkard, D. Ratkowsky, and C. L. Mohammed. 2017. Impacts of Teratosphaeria leaf disease on plantation Eucalyptus globulus productivity. Forest Pathology **47**:e12310.

Smith, G. S., F. Ascui, A. P. O'Grady, and L. Pinkard. 2020. Opportunities for Natural Capital Financing in the Forestry Sector. CSIRO, Hobart.

Spassiani, A. C. 2020. Climatology of severe convective wind gusts in Australia. The University of Queensland, The University of Queensland.

Steffen, W. 2009a. Australia's biodiversity and climate change. Csiro Publishing.

Steffen, W. 2009b. Climate Change 2009: Faster Change & More Serious Risks. Australian Government: Department of Climate Change, Canberra, Australia.

Steffen, W. 2015. Quantifying the impact of climate change on extreme heat in Australia. Climate Council of Australia Limited, Australia.

Steffen, W., and L. Hughes. 2011. The critical decade: Western Australian climate change impacts. Climate Commission Secretariat, Canberra.

Steinbauer, M. J., M. W. Short, and S. Schmidt. 2006. The influence of architectural and vegetational complexity in eucalypt plantations on communities of native wasp parasitoids: Towards silviculture for sustainable pest management. Forest Ecology and Management **233**:153-164.

Stephens, M., E. Pinkard, and R. Keenan. 2012. Plantation Forest Industry Climate Change Adaptation Handbook. Australian Forest Products Association.

Stromberg, J. C., R. Tiller, and B. Richter. 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. Ecological Applications **6**:113-131.

Sutherst, R. W., R. H. A. Baker, S. M. Coakley, R. Harrington, D. J. Kriticos, and H. Scherm. 2007. Pests Under Global Change – Meeting Your Future Landlords? Pages 211-226 *in* J. G. Canadell, D. E. Pataki, and L. F. Pitelka, editors. Terrestrial Ecosystems in a Changing World. Springer, Berlin, Heidelberg.

Tan, X., S. X. Chang, and R. Kabzems. 2005. Effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest long-term soil productivity study. Forest Ecology and Management **217**:158-170.

Tasmanian Government: Department of State Growth. 2017. Tasmania’s Forest Management System: An Overview (2017). Hobart, Tasmania.

Tepley, A. J., E. Thomann, T. T. Veblen, G. L. Perry, A. Holz, J. Paritsis, T. Kitzberger, and K. Anderson-Teixeira. 2018. Influences of fire–vegetation feedbacks and post-fire recovery rates on forest landscape vulnerability to altered fire regimes. Journal of Ecology **106**:1925-1940.

Teskey, R., T. Wertin, I. Bauweraerts, M. Ameye, M. A. McGuire, and K. Steppe. 2015. Responses of tree species to heat waves and extreme heat events. Plant, cell & environment **38**:1699-1712.

Thorn, S., C. Bässler, R. Brandl, P. J. Burton, R. Cahall, J. L. Campbell, J. Castro, C.-Y. Choi, T. Cobb, D. C. Donato, E. Durska, J. B. Fontaine, S. Gauthier, C. Hebert, T. Hothorn, R. L. Hutto, E.-J. Lee, A. B. Leverkus, D. B. Lindenmayer, M. K. Obrist, J. Rost, S. Seibold, R. Seidl, D. Thom, K. Waldron, B. Wermelinger, M.-B. Winter, M. Zmihorski, and J. Müller. 2018. Impacts of salvage logging on biodiversity: A meta-analysis. Journal of Applied Ecology **55**:279-289.

Torralba, V., F. J. Doblas-Reyes, and N. Gonzalez-Reviriego. 2017. Uncertainty in recent near-surface wind speed trends: a global reanalysis intercomparison. Environmental Research Letters **12**.

van der Meulen, A. W., and B. M. Sindel. 2008. Identifying and exploring pathways of weed spread within Australia: a literature review. University of New England.

Vasic, V., B. Konstantinovic, and S. Orlovic. 2012. Weeds in forestry and possibilities of their control. INTECH Open Access Publisher.

Vertessy, R. A., T. J. Hatton, R. G. Benyon, and W. R. Dawes. 1996. Long-term growth and water balance predictions for a mountain ash (Eucalyptus regnans) forest catchment subject to clear-felling and regeneration. Tree Physiology **16**:221-232.

Virtue, J. G., S. J. Bennett, and R. P. Randall. 2004. Plant introductions in Australia: how can we resolve 'weedy'conflicts of interest. Pages 42-48 *in* Proceedings of the 14th Australian Weeds Conference.

Virtue, J. G., and R. L. Melland. 2003. The Environmental Weed Risk of Revegetation and Forestry Plants. Department of Water, Land and Biodiversity Conservation, South Australia.

von Lützow, M., and I. Kögel-Knabner. 2009. Temperature sensitivity of soil organic matter decomposition—what do we know? Biology Fertility of soils **46**:1-15.

Wagner, R. G., G. H. Mohammed, and T. L. Noland. 1999. Critical period of interspecific competition for northern conifers associated with herbaceous vegetation. Canadian Journal of Forest Research **29**:890-897.

Walsh, K., C. J. White, K. McInnes, J. Holmes, S. Schuster, H. Richter, J. P. Evans, A. Di Luca, and R. A. Warren. 2016. Natural hazards in Australia: storms, wind and hail. Climatic Change **139**:55-67.

Warcup, J. H. 1991. The fungi forming mycorrhizas on eucalypt seedlings in regeneration coupes in Tasmania. Mycological Research **95**:329-332.

Wardlaw, T. 1990. Changes in forest health associated with short-term climatic fluctuation. Tasforests **2**.

Wardlaw, T. 2001. Mycosphaerella leaf blight of Eucalyptus globulus in the Circular Head area. Forestry Tasmania, Hobart.

Wardlaw, T. 2018. When the forest stopped growing: estimating the impact of the November 2017 heatwave on productivity of Tasmania's tall eucalypt forests. Forest Knowledge.

Wardlaw, T. 2019. An investment plan for research, development and extension to minimise threats from forest damage agents. GRC061-1819, Forest and Wood Products Australia, Melbourne.

Wardlaw, T., N. Cameron, A. Carnegie, S. Lawson, and T. Venn. 2018. Costs and benefits of a leaf beetle Integrated Pest Management (IPM) program. I. Modelling changes in wood volume yields from pest management. Australian Forestry **81**:46-52.

Wardlaw, T., L. Jordan, and K. Wotherspoon. 2011. A synthesis of the key issues in the current management of leaf beetles and proposed enhancements to the leaf beetle IPM. Forestry Tasmania: Division of Forest Research and Development Technical Report 12/2011, Hobart.

Wardlaw, T. J., and C. Palzer. 1988. Regeneration of <I>Eucalyptus</I> Species in an Eastern Tasmanian Coastal Forest in the Presence of <I>Phytophthora cinnamomi</I>. Australian Journal of Botany **36**:205-215.

Watt, M. S., M. R. Davis, P. W. Clinton, G. Coker, C. Ross, J. Dando, R. L. Parfitt, and R. Simcock. 2008. Identification of key soil indicators influencing plantation productivity and sustainability across a national trial series in New Zealand. Forest Ecology and Management **256**:180-190.

Webb, A., B. Jarrett, and L. Turner. 2007. Effects of plantation forest harvesting on water quality and quantity: Canobolas State forest, NSW.*in* Proceedings of the 5th Australian Stream Management Conference: Australian Rivers: Making a Difference, Charles Sturt University, Thurgoona, Australia.

White, D. A., D. S. Crombie, J. Kinal, M. Battaglia, J. F. McGrath, D. S. Mendharn, and S. N. Walker. 2009. Managing productivity and drought risk in Eucalyptus globulus plantations in south-western Australia. Forest Ecology and Management **259**:33-44.

Wilkinson, G. R., and W. A. Neilsen. 1995. Implications of early browsing damage on the long term productivity of eucalypt forests. Forest Ecology and Management **74**:117-124.

Williams, A. A. J., and D. J. Karoly. 1999. Extreme fire weather in Australia and the impact of the El Nino Southern Oscillation. Australian Meteorological Magazine **48**:15-22.

Williams, J. A., and C. J. West. 2000. Environmental weeds in Australia and New Zealand: issues and approaches to management. Austral Ecology **25**:425-444.

Williams, K., R. Ford, I. Bishop, and E. Smith. 2012. Evaluating different ways of managing forested landscapes. Reshaping environments: an interdisciplinary approach to sustainability in a complex world. Cambridge University Press.

Williams, K. J. H. 2014. Public acceptance of plantation forestry: Implications for policy and practice in Australian rural landscape. Land Use Policy **38**:346-354.

Williams, M. C., and G. M. Wardle. 2007. Pinus radiata invasion in Australia: Identifying key knowledge gaps and research directions. Austral Ecology **32**:721-739.

Wills, A. J., and J. D. Farr. 2017. Gumleaf skeletoniser Uraba lugens (Lepidoptera: Nolidae) larval outbreaks occur in high rainfall Western Australian jarrah (Eucalyptus marginata) forest after drought. Austral Entomology **56**:424-432.

Woldendorp, G., M. J. Hill, R. Doran, and M. C. Ball. 2008. Frost in a future climate: modelling interactive effects of warmer temperatures and rising atmospheric [CO2] on the incidence and severity of frost damage in a temperate evergreen (Eucalyptus pauciflora). Global Change Biology **14**:294-308.

Wood, M. J., R. Scott, P. W. Volker, and D. J. Mannes. 2008. Windthrow In Tasmania, Australia: Monitoring, Prediction And Management. Forestry: An International Journal of Forest Research **81**:415-427.

Wu, H. X., K. G. Eldridge, A. C. Matheson, M. B. Powell, T. A. McRae, T. B. Butcher, and I. G. Johnson. 2007. Achievements in forest tree improvement in Australia and New Zealand 8. Successful introduction and breeding of radiata pine in Australia. Australian Forestry **70**:215-225.

Ximenes, F., H. Bi, N. Cameron, R. Coburn, M. Maclean, D. Sargeant, M. Mo, S. Roxburgh, M. Ryan, J. Williams, and K. Boer. 2016. Carbon stocks and flows in native forests and harvestedwood products in SE Australia. Forest & Wood Products Australia: PNC 285-1 112.

Ximenes, F., M. Stephens, M. Brown, B. Law, M. Mylek, J. Schirmer, A. Sullivan, and T. McGuffog. 2017. Mechanical fuel load reduction in Australia: a potential tool for bushfire mitigation. Australian Forestry **80**:88-98.

Yanoviak, S. P., E. M. Gora, J. M. Burchfield, P. M. Bitzer, and M. Detto. 2017. Quantification and identification of lightning damage in tropical forests. Ecology and Evolution **7**:5111-5122.

Yasmin, S., and D. D'Souza. 2010. Effects of pesticides on the growth and reproduction of earthworm: a review. Applied and Environmental soil science **2010**.

Zeng, Z. Z., A. D. Ziegler, T. Searchinger, L. Yang, A. P. Chen, K. L. Ju, S. L. Piao, L. Z. X. Li, P. Ciais, D. L. Chen, J. G. Liu, C. Azorin-Molina, A. Chappell, D. Medvigy, and E. F. Wood. 2019. A reversal in global terrestrial stilling and its implications for wind energy production. Nature Climate Change **9**:979-+.

Zhang, L., W. R. Dawes, and G. R. Walker. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research **37**:701-708.

Acknowledgments

The authors thank Tim Wardlaw for reviewing sections of the report and for insightful discussions