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Reconciling timber harvesting, biodiversity conservation and carbon sequestration in Queensland, Australia

Tyron J. Venn *

School of Agriculture and Food Sciences, The University of Queensland, St Lucia, QLD 4072, Australia

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ABSTRACT

In many countries, forest policies have been enacted that reduce opportunities for public and private native forests to be sustainably managed for multiple uses, including timber production. Such policies have typically been implemented out of concern for the environment, but policy-makers often make poor assumptions about or ignore the associated perverse ecological and economic trade-offs that can threaten global action to conserve biodiversity and mitigate climate risk. The purpose of this paper is to inform and promote research on the application of the land sharing–sparing framework to better accommodate ecological and economic trade-offs in forest policy evaluation. The regional context is Queensland (QLD), Australia, where consideration is being given to policy changes that will substantially increase land sparing within the public and private native forest estate by contracting the area available for management under land sharing with selection timber harvesting. A modified conceptualisation of the land sharing–sparing framework is introduced, which explicitly accounts for the role that international trade can play in facilitating domestic land sparing policy. Critical reviews of literature concerning six important ecological and economic trade-offs that are associated with domestic forest policy are presented: (a) international biodiversity conservation; (b) climate risk mitigation; (c) securing domestic wood supply; (d) resourcing domestic forest management; (e) management of wildfire risk; and (f) domestic biodiversity conservation. Under existing policy settings, increased land sparing in QLD has a high risk of unintended negative outcomes, including for international biodiversity conservation and carbon emissions. While land sparing can benefit species that require long undisturbed forest habitat, conservation of most native flora and fauna in QLD is not substantially affected or is enhanced by selection harvesting practices permitted in the state. Decades of poor government resourcing of conservation estate management and timber plantation expansion suggests increased land sparing will have negligible benefits for domestic biodiversity conservation and wood supply in the absence of a considerable and permanent reallocation of scarce resources. In contrast, land sharing can provide greater long-term climate risk mitigation benefits, promote high biodiversity values through creation of heterogeneous landscape mosaics and leverage private sector resources for conservation activities. These complex ecological and economic trade-offs have been collated for the first time in an Australian context and justify further research to explore their quantification and accommodation within the land sharing–sparing framework to better inform forest policy-making.

1. Introduction

In Europe, North America and Australia, timber harvesting in native forests has been politically charged for decades, with numerous conflicts between environmental groups, the timber industry and government agencies over the impacts of timber production on biodiversity (Cubbage et al., 1993; Dargavel, 1995; Hellström, 1999; Furness et al., 2015; Davey, 2018a). Australia's National Forest Policy Statement (Commonwealth of Australia, 1992) recognises the need for a sound scientific basis for sustainable forest management, efficient forest use, and provision of other social and conservation objectives. However, opportunities for sustainable harvesting in native forests of Australia have often been overtaken by domestic politics that play to key ideological symbols and short-term political interests, rather than according to scientific evidence and the long-term national and global interests (Kanowski, 2017; Dargavel, 2018; Deegen, 2019; Jackson et al., 2021; Forestry Australia, 2022). This has been exacerbated by confusion about the environmental impacts of forestry due to:

* Corresponding author.
E-mail address: t.venn1@uq.edu.au.

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a) low public awareness, including a false understanding that biodiversity can only be protected by prohibiting timber harvesting (Florence, 1996; Wilkinson, 2006; Edwards et al., 2014b; Matysek and Fisher, 2016);
b) government statistics that record forestry as a form of land clearing alongside urban, mining and agricultural developments (Metcalfe and Bui, 2016; Curtis et al., 2018; Anon, 2021);
c) the media providing similar levels of coverage to both published, peer reviewed scientific research and unsubstantiated assertions made by individuals with no formal science qualifications (e.g. Honan, 2021); and
d) instances of false or unsupported claims about native forest management published in peer-reviewed scientific journals (Poynter and Ryan, 2018).[1]

The economic reality is that rural land is managed for mineral, crop, livestock and timber production because of domestic and international demand for these goods. When a government implements policies to limit domestic native forest timber production, the excess domestic timber demand will be satisfied by a combination of substitution with domestic plantation timber (for some product types if there is excess supply), increased production of substitute products with substantially higher levels of embedded carbon (e.g. steel, aluminium, plastic, brick, concrete, and carpet) (Sathre and O'Connor, 2010), and increased plantation and native forest timber imports that can drive forest degradation and rural land use change in developing and other producer countries (Meyfroidt et al., 2010; Seto et al., 2012; Petrokofsky et al., 2015a; Moran and Kanemoto, 2017; Pendrill et al., 2019; Hoang and Kanemoto, 2021). Timber importing nations can falsely appear to be more ecologically sustainable at the regional scale, with governments and consumers rarely taking responsibility for, or even being aware of, the environmental damage and ecosystem changes that occur in the country from where their wood originates (Kastner et al., 2011; Mills Busa, 2013).

The ecological reality is that, in a world where biodiversity is threatened by climate change, habitat fragmentation, invasive species and uncharacteristic disturbance regimes, conservation will often require active management and diverse disturbance regimes in space and time (Stanturf et al., 2014; Kearney et al., 2018; Belmonte et al., 2019; Jackson et al., 2021; Ward et al., 2021). Unfortunately, conservation estate management is often chronically under-funded (Watson et al., 2014; Queensland Treasury Corporation, 2018), resulting in adoption of a non-intervention strategy sometimes described as 'benign neglect' (Brown, 1996). Opportunities for biodiversity conservation in forests managed sustainably for timber production to complement the strict conservation estate need to be evaluated if well-informed decisions are to be made. This paper considers the ecological and economic trade-offs associated with selection timber harvesting in native forests in the Australian state of Queensland (QLD). The state has 51.6 million hectares of native forest (39% of the national total), some of which are commercially important and available for selection harvesting under existing forest policy (ABARES, 2018).

Forest policy is developed by governments to reflect 'social choices' to guide how forest resources will be managed over time to achieve a stated or implicit objective (Cubbage et al., 1993). Since establishment of the QLD Forest Service in 1906, forest policy in QLD had promoted selection harvesting systems in public and private native forests to supply the hardwood industry, provide income diversification opportunities for farmers, and generate substantial levels of employment and income in regional areas (Carron, 1985; DPI Forestry, 1998; Queensland Department of Agriculture and Fisheries, 2016). In 1999, a land sparing agreement was struck between conservationists, the timber industry and the QLD Government in the South East QLD Forest Agreement, a highly politicised institutional response to conflict over the allocation, use and management of state-owned native forests (Queensland CRA/RFA Steering Committee, 1999; Lane, 2003; McAlpine et al., 2005). This included the immediate transfer of 53% of state-owned timber production native forests to protected area status, with harvesting permitted in the remainder until 2024, while a substitute long-rotation (25 to 30 years) hardwood plantation resource was established (McAlpine et al., 2005; GHD, 2015). The hardwood plantations have failed, the QLD Government is considering options to transfer more of the state-owned timber production native forests to protected area status, and the hardwood timber industry is becoming increasingly reliant on private native forests (GHD, 2015; Burgess and Catchpoole, 2016; Matysek and Fisher, 2016; Venn et al., 2021), where sovereign risk has long been a serious impediment to investment in sustainable management (Queensland CRA/RFA Steering Committee, 1998b; Bureau of Rural Sciences, 2004; Dare et al., 2017; Downham et al., 2019; Francis et al., 2020).

In 2021, a Native Timber Advisory Panel was established to advise the QLD Government on policy options for the native forest hardwood timber industry (Queensland Department of Agriculture and Fisheries, 2021). In essence, forest policy-makers in QLD are attempting to optimise the mix of forestland allocated to conservation, extensive (i.e. selection harvesting systems in native forests) and intensive (i.e. exotic and native species plantations) management. This decision space can be well-represented by the land sharing–sparing framework, which facilitates understanding and quantification of commodity production and biodiversity conservation trade-offs between alternative region-wide land-use scenarios (Finch et al., 2020). Comprehensive reviews of empirical applications have revealed that the framework holds much promise to inform improved land management decision-making, as an alternative to more common ad-hoc, and politically-based approaches (Balmford, 2021; Betts et al., 2021; Sidemo-Holm et al., 2021).

The purpose of this paper is to promote research to support the application of the land sharing–sparing framework to inform development of evidence-based, ecologically sustainable and socio-economically efficient forest policy in QLD. Inspired by Grau et al. (2013), a modified form of the land sharing–sparing framework that explicitly accommodates international impacts of domestic forest policy is described in the following section. Applying this framework in QLD requires context-specific empirical research to:

1. better understand and quantify the ecological and economic trade-offs between land sharing and sparing;
2. establish reference conditions against which ecological outcomes under alternative forest management approaches can be evaluated; and
3. develop a decision support tool to evaluate the ecological and economic performance of forest policies over space and time.

In the absence of a research program, this paper presents the first comprehensive review of literature to highlight the complex trade-offs associated with alternative forest policies in an Australian context. It was necessary to take a broad scope because discussions about forest management and policy in Australia routinely fail to adequately consider the important and complex implications for international biodiversity conservation, domestic biodiversity conservation, climate risk mitigation, securing domestic wood supply, resourcing domestic forest management, and mitigating wildfire risk. Finally, the paper makes recommendations about research methods to establish ecological reference conditions and the development of an integrative decision support tool to facilitate application of the land sharing–sparing framework.

[1] Unlike China, Canada, Japan, the United States, and many European countries, Australia does not have a national office for research integrity (Worthington, 2022).

Although the paper has an Australian focus, international readers will find insights relevant to other contexts. Many nations import substantial volumes of wood products, and the modified conceptualisation of the land sharing–sparing framework presented is necessary in these contexts to explicitly account for the ecological footprint of international trade, which can facilitate domestic land sparing. The section on climate risk mitigation reviews international literature on the carbon benefits of managing forests for production and strict conservation, and explains why empirical literature has come to opposing conclusions. Sharing–sparing practitioners have frequently given limited consideration to economics in their analyses; however, this review has identified critical implications of public and private resourcing (e.g. trained personnel and equipment), private property rights and opportunity costs on the effectiveness of sharing and sparing policies to deliver domestic biodiversity and timber production outcomes. Similar economic relationships likely exist in international contexts and failure to adequately account for them represents a serious limitation of the utility of the sharing-sparing framework. The sharing-sparing trade-offs for conservation of flora, mammals, birds, reptiles and amphibians in an Australian context can inform discussion and development of global strategies to conserve biodiversity.

2. Modified conceptualisation of the land sharing–sparing framework to accommodate the international ecological footprint of domestic forest policy

The land sharing–sparing framework arose in literature pertaining to biodiversity conservation–agricultural production trade-offs (Balmford et al., 2005; Green et al., 2005; Dorrough et al., 2007; Phalan et al., 2011), but has been increasingly applied to biodiversity conservation–forestry trade-offs (Law et al., 2017; Runting et al., 2019; Betts et al., 2021; Himes et al., 2022). The typical application optimises allocation of land to alternative uses to maximise biodiversity conservation, subject to maintaining a particular level of commodity production (Betts et al., 2021). In the forestry context, extensive management in native forests with selection harvesting systems is an example of land sharing. Wood products can be produced jointly with biodiversity conservation, although some biodiversity may be disadvantaged in particular places at particular times relative to non-harvested conservation forests. Conversely, disturbance associated with selection harvesting and silvicultural treatments will advantage some biodiversity. Intensively managed timber plantations allow for land-sparing; the plantation conservation benefit hypothesis (Pirard et al., 2016). Relative to selection harvesting in native forests, a smaller plantation area is required to supply the market with the same timber volume, which allows more native forest to remain unharvested and be allocated to the conservation estate. The conservation estate is often land tenure-based (e.g. National Parks on public land and Nature Refuges on private land in QLD), but can also be achieved through legislated restrictions on private property rights. An important trade-off with land sparing is that plantation forests are typically biologically depauperate relative to native forests managed under selection harvesting regimes (Norman et al., 2004; Chaudhary et al., 2016). Furthermore, in the Australian context, native forests produce a suite of unique hardwood timbers with desirable properties for high-value products that cannot be supplied by Australian softwood or hardwood plantations (IFA / AFG Board, 2020).

Fig. 1 provides abstract illustrations of contrasting domestic forest policies ranging from land sharing (policy A) to land sparing (policy E). Earlier literature focussed on land sharing or sparing strategies exclusively, but recent studies have incorporated a triad approach, or intermediate strategy, which mixes land sharing and land sparing (Betts et al., 2021; Himes et al., 2022). The triad is illustrated by policy B. Policies C and D are proposed additions to the framework described below. The domestic conservation estate area is maximised by policy E, although the area of native vegetation (extensively managed and conservation forest) is maximised by policy A. In the standard conceptualisation of the land sharing–sparing framework, alternative target levels of domestic timber production are proposed, and domestic forest management and biodiversity conservation outcomes associated with each of these production levels are simulated for policies A, B and E. The domestic socio-economic impacts can then be traded off against domestic environmental outcomes at the landscape-scale over time. International ecological and economic impacts of alternative domestic production levels are not explicitly accommodated within the framework. However, in open economies, trade in wood products is common and imported wood volumes are likely to increase when domestic production falls.

Practitioners of land sharing–sparing have identified several necessary improvements to the standard conceptualisation, including joint consideration of additional environmental and socio-economic costs and benefits (Tisdell, 2015; Balmford et al., 2018a; Balmford, 2021; Betts et al., 2021; Sidemo-Holm et al., 2021). Grau et al. (2013) highlighted the need to accommodate the potential global benefits of changes in the spatial and temporal distribution and abundance of domestic forest biodiversity to avoid biodiversity losses and carbon emissions embodied in imported wood products or the manufacture of non-wood substitutes. This suggests application of the land sharing–sparing framework can be improved by optimising the domestic and international allocation of land to alternative uses to satisfy domestic consumer demand. Fig. 1 indicates an accounting for the international forest management impacts of domestic forest policy. The introduction of policy options C and D permits comparison of the global economic and ecological outcomes of domestic policies that achieve lower domestic production targets. Policies C and D increase the domestic conservation estate area relative to policies A and B; however, this is accompanied by a greater impact on international forest than is the case with policies A, B and E.

3. Implications of domestic land sparing on international biodiversity conservation

Prior to the Second World War, land sharing was the forest management paradigm in Australia. There was a transition to policy B (see Fig. 1) after the War, and since the 1980s forest policy throughout Australia has shifted towards policy C. The state governments of Victoria (VIC) and Western Australia (WA) have announced transition to policy D within the decade. Policies C and D are unlikely to generate global net gains in biodiversity conservation and carbon sequestration (Gan and McCarl, 2007). Even if the transitions in VIC and WA are accompanied by a large plantation expansion program, there will be a 25 to 30-year period of policy D until policy E can be achieved. As discussed in Section 5, policy E requires displacement of other productive agricultural land uses and is unlikely to be achievable in Australia without considerable long-term government investment. International impacts need to be better accommodated in domestic forest policy analysis.

As Australia's population grew by 39% over the period 1996 to 2018, total domestic softwood and hardwood sawlog and veneer log production decreased from 0.84 m^3/capita to 0.65 m^3/capita (ABARES, 2022). A major contributor to this decline was the transition in most Australian states away from policy B toward policies C and D. Publicly-owned production native forests were transferred to the conservation estate, and domestic native hardwood sawlog and veneer log production fell from 4.0 million m^3/y to 1.8 million m^3/y (ABARES, 2022). Whittle et al. (2012, 2013) argued that high international leakage would likely arise from avoided harvesting in Australia's public native forests.

Estimating Australia's international forest products footprint is complicated by differences in recovery of marketable product from log volume, and trade data that does not record volume (only value) for several major imported wood product categories, including wood furniture, and builders' carpentry, mouldings and doors (ABARES, 2022). With an aim to motivate further research, Fig. 2 has been derived from Forest Trends (2017) and ABARES (2022) to provide a preliminary assessment of the roundwood equivalent (RWE) import volume of solid

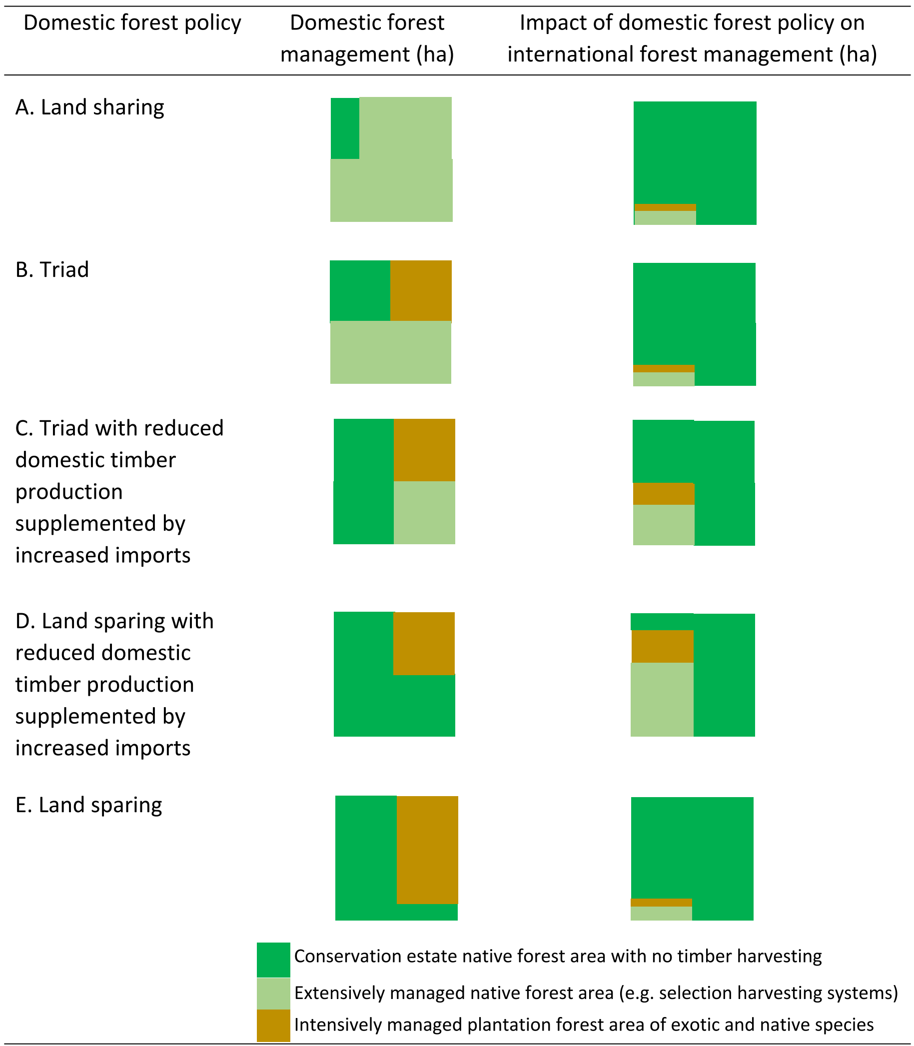

Fig. 1. Conceptual illustration of five forest policies that will satisfy domestic consumer demand for wood products by altering the area of domestic and international forests managed for conservation, extensive timber production and intensive timber production.

wood and engineered wood products (EWPs) by nation and nation groupings of product origin. It indicates an increase in imports from 2.9 million m^3/y RWE to 6.5 million m^3/y RWE over the period 1996 to 2018, representing a rise in annual consumption of imported RWE from 0.16 m^3/capita to 0.26 m^3/capita. The top-five wood imports in 2018 were sawn softwood (2.6 million m^3 RWE), EWPs (1.9 million m^3 RWE), wood furniture (1.0 million m^3 RWE), builders' carpentry, mouldings and doors (0.66 million m^3 RWE), and sawn hardwood (0.16 million m^3 RWE). Imported sawn softwood has been sourced from developed countries at relatively consistent levels over time (e.g. 2.1 million m^3 RWE in 1996). At least 50% of all other products have been imported from China and other developing countries, including greater than 90% of wood furniture. Although the annual imported volume of sawn hardwood decreased by 0.11 million m^3 RWE between 1996 and 2018, annual imports of products that utilise hardwoods have increased. For example, annual imports of EWPs have increased by 1.5 million m^3 RWE, wood furniture by 0.85 million m^3 RWE, and builders' carpentry, mouldings and doors by 0.51 million m^3 RWE over the same time period. In total, Australia imported about 98 million m^3 RWE in solid wood products and EWPs over the period 1996 to 2018.

The increase in Australian demand for imported solid wood products and EWPs since 1996 has largely been met by developing countries (0.5 million m^3 of RWE in 1996, and 2.4 million m^3 of RWE in 2018) (derived from ABARES, 2022). Illegal logging is responsible for up to 30% of global timber production, and 50% to 90% of harvesting in many tropical countries (INTERPOL, 2019). The primary impacts of timber harvesting (e.g. tree felling, snigging and roading) in developing countries often facilitate far more severe and enduring secondary (non-forestry) impacts, including illegal and planned land clearing radiating out from logging roads (Putz, 2011; Edwards et al., 2014b; Brandt et al., 2016). There is evidence that large volumes of a popular imported substitute for QLD native forest hardwood decking, merbau (*Intsia* spp.), are being illegally and unsustainably harvested in Indonesia, Malaysia, Papua New Guinea, and Pacific Island nations (Tong et al., 2009; Shearman et al., 2012; Riddle, 2014; Anon, 2020; Ng et al., 2020).

Australia imported 1.2 million m^3 of RWE wood products from China in 2016, half of which was wood furniture (Forest Trends, 2017). In that year, China imported 29.6 million m^3 of RWE hardwood timber, including 77% from countries with high risk of poor governance and corrupt institutions that are associated with high levels of illegal logging and broader land clearing, including Papua New Guinea, Solomon Islands, Cambodia, Myanmar, Laos, Malaysia, Thailand, Republic of Congo, and Ghana (Forest Trends, 2017; Yi, 2019; Guan et al., 2020; Siriwat and Nijman, 2023). Demand for wood products from China is positively correlated to loss of forest cover in the low and middle-income countries from which China sources its wood (Fuller et al., 2018; Shandra et al., 2019).

Australia imported 0.64 million m^3 of RWE from Indonesia and

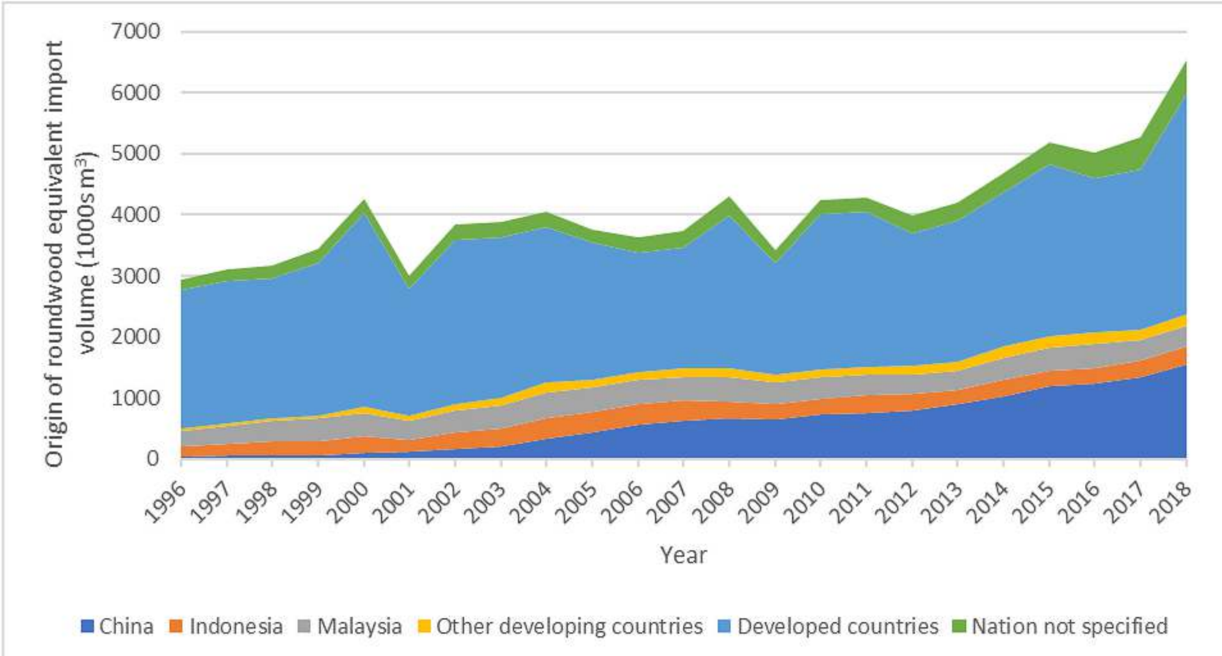

Fig. 2. Australian roundwood equivalent import volume by country of origin from 1996 to 2018.
Notes: RWE volume has been estimated from ABARES (2022) volume import data for roundwood, sawnwood (hardwood and softwood) and EWPs (veneer, plywood and particleboard), and value import data for wood furniture and miscellaneous wood products (including mouldings and doors, builder's carpentry and parquet flooring, and household articles such as frames, utensils, ornaments, tools and tool handles). RWE volume for sawnwood assumes a recovery rate of 35% from log volume for hardwood and softwood logs. RWE volume for EWPs assume a recovery rate of 50% from log volume. ABARES (2022) reported wood furniture and miscellaneous wood product imports in Australian dollars at $2.1 billion and $1.6 billion in 2018, respectively. Import RWE volume to value ratio for imported furniture from China in 2016 was 496 m^3 RWE/million Australian dollars, and for all miscellaneous wood products averaged 530 m^3 RWE/million Australian dollars, but was 670 m^3 RWE/million Australian dollars for builders' carpentry, mouldings and doors (Forest Trends, 2017). These ratios were used to convert inflation-adjusted Australian dollar import values for all years to RWE volume. In 2018, China accounted for 65% of wood furniture imports and other developing countries accounted for a further 25%. In 2018, China accounted for 28% of miscellaneous wood product imports, and other developing countries a further 30%.

Malaysia in 2018. Historically, a large proportion of timber produced in Indonesia has been illegally harvested, with the World Resources Institute reporting that 219 million m^3 of illegally-sourced wood was harvested there over the period 1991 to 2014 (Chitra and Cetera, 2018). The most recent attempt by Indonesian authorities to address illegal logging is the Timber Legality and Sustainability Verification System (Sistem Verifikasi Legalitas dan Kelestarian, SVLK), which was introduced in 2009 to facilitate Indonesia's participation in trade in legal timber through a Voluntary Partnership Agreement (VPA) under the European Union (EU) Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan (Susilawati and Kanowski, 2022). However, the SVLK system is regularly bypassed and levels of illegal timber harvesting in Indonesia remain high (World Bank, 2019; Susilawati and Kanowski, 2022; Berenschot et al., 2023), with illegal Indonesian wood products arriving in the EU directly and indirectly via less regulated countries, including China (Partzsch et al., 2023). Demand for solid wood products and EWPs from Indonesia and Malaysia has been linked to the decline of the orangutan, Malayan tiger, Asian sunbear and Asian tapir (Jamhuri et al., 2018; Pandong et al., 2019; Sapari et al., 2019; Namkhan et al., 2021). One month after the September 2021 announcement of the shutdown of native forest timber production from state-owned lands in WA, local furniture makers were already looking to import substitute timber from Indonesia (Mackintosh, 2021).

The Federal Government of Australia budgeted $0.9 million in 2021–22 to assess Australia's exposure to illegally harvested timber imports (Frydenberg and Birmingham, 2021).[2] By contributing to international demand for wood products from developing countries, Australian consumption is likely to encourage illegal logging, deforestation and biodiversity decline (Lenzen et al., 2012; Taylor et al., 2016; Kitzes et al., 2017; Moran and Kanemoto, 2017; Chaves et al., 2020; Shigetomi et al., 2020) regardless of whether Australian imports from these nations are legally sourced. Further research is necessary to quantify the ecological footprint of Australian wood imports and account for the footprint within domestic forest policy-making.

4. Climate risk mitigation trade-offs associated with land sharing and sparing

Fully decarbonising global industry is a central part of achieving climate stabilisation under the Paris Agreement's goal of limiting warming to less than 2 degrees Celsius (Rissman et al., 2020). Internationally, the construction sector is responsible for a large fraction of greenhouse gas emissions, with concrete and steel production together representing about 10% of total global emissions (Davis et al., 2018; Shanks et al., 2019). There is strong evidence that wood products are associated with lower lifecycle carbon emissions when compared to products made from non-renewable or emissions-intensive materials such as steel, concrete, plastic, brick and carpet (Sathre and O'Connor, 2010; Lu et al., 2017; Leskinen et al., 2018; Sandanayake et al., 2018; Rissman et al., 2020; D'Amico et al., 2021; Verkerk et al., 2021). However, focus areas for the QLD Government to manage risks and realise opportunities associated with climate change and the transition to a zero net emissions economy excluded forestry and wood products, and promoted low-carbon cement and steel to decarbonise the construction sector (Ernst and Young, 2019a, 2019b).

The Intergovernmental Panel on Climate Change (IPCC) has long argued that forest management aimed at maintaining or increasing

[2] All reported dollar amounts are Australian dollars.

forest carbon stocks, while producing an annual sustained yield of timber, fibre and energy, will generate the largest sustained climate risk mitigation benefit from forests (Metz et al., 2007). There are four main carbon benefits of forests managed for timber (Lippke et al., 2014; Williams et al., 2016; Köhl et al., 2020). First, the harvested logs can be transformed into wood products that store carbon off-site for many decades in use (e.g. electricity distribution poles, structural timber and engineered wood products), while freeing up growing space within the forest for regeneration to sequester more carbon. Furthermore, at the end-of-their useful life, wood products can store substantial volumes of carbon for long time periods if disposed in landfills (Ximenes et al., 2015; Ximenes et al., 2019). Second, wood products from sustainably managed forests can displace high embodied carbon substitutes (e.g. steel and concrete) and avoid carbon emissions from unsustainably managed forests that would otherwise supply substitute wood products. Third, thinned trees from silvicultural treatments, harvest residues in the forest, and residues at the mill can potentially be utilised to help meet energy needs by recycling biosphere carbon and avoiding fossil fuels that transfer geologic carbon to the biosphere. Fourth, there are climate risk mitigation benefits of having a diversified portfolio of forest carbon sinks through land sharing, including wood products, displaced substitute products and energy, which are less susceptible to disturbances such as wildfires and cyclones than carbon stored on-site only via land sparing. Offsetting these gains from wood utilisation are fossil fuel emissions from the harvest, transport and processing of the logs, the decay of forest and mill residues, and the foregone higher level of carbon stored in living (unharvested) biomass in conservation forest.

Empirical literature on carbon balances of forests managed for conservation and timber production have come to opposing conclusions (e.g. Krankina et al., 2012; Peckham et al., 2012). To a large extent, this reflects the carbon accounting framework adopted, scope of the analysis, adequacy of data used, and localised conditions. The choice of accounting framework is particularly important; for example, the Kyoto framework does not account for carbon storage in landfill, avoided carbon emissions embodied in substitutes (e.g. steel, concrete and wood from unsustainably managed forests) and avoided fossil fuel emissions by using biomass for energy (UNFCCC, 2008; IPCC, 2013). The Australian National Carbon Accounting System (NCAS) does account for carbon stored in landfill, but not avoided emissions in substitutes and avoided fossil fuel consumption (Australian Government Department of Industry, Science, Energy and Resources, 2020, 2021). In contrast, a life cycle assessment (LCA) takes into account all relevant carbon emissions and removals, which represents the best approximation of actual atmospheric impacts. The potential for emissions from poor land sharing forest management practices to outweigh the benefits of utilising wood is not disputed, which is why it is critical to apply an LCA to comprehensively assess net carbon sequestration attributed to forest management and the timber industry on a case-by-case basis (Moroni, 2013; Dugan et al., 2018; Leskinen et al., 2018). Life cycle carbon implications of forest management will vary depending on (i) forest growth rates, (ii) natural disturbance regimes, (iii) forest management practices, (iv) enforcement of property rights to forest land (which affects the level of secondary impacts of harvesting in developing countries), (v) level of sovereign risk (which affects landholder incentives to manage forest in developed and developing countries), (vi) markets for timber (influenced by wood properties and economic factors such as mill-delivered log cost and distance to markets), which affects species, log types and volumes harvested, as well as the wood products manufactured, (vii) efficiency of wood processing industries (in terms of energy inputs and the recovery of product from log volume), and (viii) the atmospheric impacts of using wood and non-wood substitute products.

Researchers in Australia and internationally who have concluded land sparing will generate superior climate outcomes have typically adopted a partial carbon accounting framework, such as Kyoto (Colombo et al., 2012; Dean et al., 2012; Krankina et al., 2012; Perkins and Macintosh, 2013; Keith et al., 2014; Mackey et al., 2020; Frontier Economics and Macintosh, 2021; Mackey et al., 2022). Researchers who have adopted the LCA approach have typically found land sharing generates net carbon sequestration benefits relative to land sparing (Kaul et al., 2010; Peckham et al., 2012; Klein et al., 2013; Oliver et al., 2014; Sasaki et al., 2016; Gustavsson et al., 2017; Suter et al., 2017; Morrison Vila et al., 2021). A lifecycle assessment has not been performed for native forest management in QLD, although studies in northern New South Wales (NSW) with similar climate, forest types, selection harvest regimes and hardwood industry structure, have revealed land sharing will sequester more carbon over time than land-sparing (Ximenes et al., 2012; Ximenes et al., 2016). These findings are complemented by Australian research that has shown substantial carbon emissions reduction can be achieved by using more wood products in construction (Yu et al., 2017), including halving the lifecycle emissions of detached houses (Carre, 2011; Ximenes and Grant, 2013) and reducing the lifecycle emissions of midrise residential buildings by one-third (Jayalath et al., 2020). In forest-poor Asian nations, including Taiwan, Japan and South Korea, Australian wood products for construction are considered among the most sustainable, and as having lower embodied carbon than equivalent wood products from the USA, China, Malaysia, Brazil and Russia (Li et al., 2018). A LCA of the carbon balance of native forests managed for conservation and timber production in QLD is warranted.

5. Securing domestic wood supply through land sharing and sparing

The economic rationale for government agencies in many nations around the world actively managing native and plantation forests on public land for timber production during the 19th and 20th centuries was that timber could not be sustainably supplied by the private sector due to low rates of return and long payback periods (Carron, 1985; Dargavel, 1995; Loomis, 2002). Indeed, a precondition for Australia's two major plantation expansion phases was considerable direct and indirect federal government investment (de Fegely et al., 2011; Burns et al., 2015). Australia's softwood and hardwood plantation area peaked at just over 2 million hectares in 2011–12 (Whittle et al., 2019); however, the estate had declined to 1,774,660 ha by 2019–20, due to poor financial performance of hardwood plantations (Downham and Gavran, 2020; Legg et al., 2021).

Timber plantation expansion is necessary to maintain domestic wood production under land sparing forest policy. The hardwood plantation program in QLD that commenced in the aftermath of the 1999 South East QLD Forest Agreement was characterised by selection of marginal land for timber growing and poor species-site matching, which resulted in low rates of successful plantation establishment, severe disease outbreaks and slow growth rates (Forest and Timber Industry Working Group, 2012; Matysek and Fisher, 2016). Pests and diseases in native and exotic timber plantations remain a major concern to the Australian timber industry (Cameron et al., 2018; Carnegie et al., 2018; Wardlaw et al., 2018), and plantations are likely to become more susceptible with climate change projected to increase drought-induced tree mortality, wildfire risk and cyclone risk (Rhodes and Stephens, 2014). GHD (2015) projected there would be about 19,400 ha of hardwood plantations in QLD with sawlog suitable species by 2024; however, timber yield is expected to be dominated by low quality logs with limited domestic and export market opportunities, and only about 13,000 m^3/y of logs with similar wood properties to small logs sourced from native forests. This is equivalent to 10% of the production level of state-owned native forests that the plantations were intended to replace (Queensland CRA/RFA Steering Committee, 1998b).

Trade liberalisation in Australia since the 1980s means consumers have ready access to low-cost imported timber, which depresses market prices for Australian wood products (Stephens and Grist, 2014). Low rates of return and the high opportunity cost of 25 to 30 years of foregone grazing or cropping income makes it challenging to encourage landholders with suitable soils and rainfall to plant trees for sawlogs (de Fegely et al., 2011; Forest and Timber Industry Working Group, 2012; Whittle et al., 2019; Hampton, 2021). Whittle et al. (2019) estimated that only around 4770 ha of new short rotation hardwood plantations and 24,010 ha of new long-rotation softwood plantations could become economically competitive with existing agricultural land use throughout Australia by 2050. Furthermore, Australian rural communities are often in favour of native forest management for timber production, but are concerned about the economic and social impacts of expanding timber plantations, which was exacerbated by collapse of the tax-driven managed investment scheme program in the decade to 2010 (Schirmer, 2007; Schirmer and Bull, 2014; Kanowski, 2017; Kanowski and Edwards, 2021). Since the 2019–20 Black Summer Bushfires, non-industrial private plantation growers in Australia have experienced large increases in their insurance premiums or cannot obtain insurance for their plantations (Makintosh, 2022). There is limited investor interest in establishing new plantations or replanting harvested hardwood plantations in QLD (GHD, 2015; Matysek and Fisher, 2016), with total area of the latter declining by 51.6% over the period 2014–15 to 2019–20 to 17,900 ha, including a substantial fraction of these being cleared for cattle grazing prior to harvest (Legg et al., 2021).

Under the existing policy environment in Australia, increased timber production from plantations will not become available to substitute for native forest hardwoods or timber imports (Downham and Gavran, 2020). Encouraging plantation investments will require policies that facilitate partnerships between industry, landowners and government that improve their profitability through lower costs, higher productivity and additional revenue streams for growers on the basis of their broader public benefits (e.g. carbon sequestration) (de Fegely et al., 2011; Rhodes and Stephens, 2014; Stephens and Grist, 2014). However, policy-makers must be mindful of the substantial negative implications for global ecological and carbon footprints if timber imports and non-wood substitutes fill the supply gap created by land sparing policy while an expanded domestic plantation estate matures.

There are several reasons why land sharing with selection harvesting systems in QLD's native forests can overcome many economic impediments to domestic wood supply associated with plantation establishment for land sparing. First, native forests on state-owned and private land exist today because they have low opportunity cost; they are the residual lands not desired for agriculture (Carron, 1985; Dargavel, 1995). The low opportunity cost means private landholders are more likely to improve the financial performance of their business by managing their native forest areas for timber production than by establishing timber plantations on their agricultural land. This has obvious implications for likelihood of adoption of native forestry versus plantation forestry. Indeed, Cameron et al. (2019) reported that 100% of surveyed southern QLD landholders were interested in learning native forest management skills by attending field days. The low opportunity cost explains the generally much lower market value of native forest land relative to cleared agricultural land, which means upfront costs for new private or public investments in land sharing are substantially lower per hectare than for plantation establishment as part of a land sparing strategy.

Second, native forests are already established and natural regeneration can be relied on in a healthy forest ecosystem. For example, in southern Queensland there are about 1.9 million ha of commercially important and harvestable private native forests (Venn, 2020) where there is no need to expend resources on the high costs of plantation site preparation, establishment and management. Third, the uneven-aged structure of QLD's native forests means that many forest areas have mature trees ready for harvest in the near term. Fourth, the productivity of the native forest estate can be substantially increased with silviculture (Venn, 2020). Fifth, native forest management does not generate the social upheaval that can be associated with large-scale plantation establishment (Forest and Timber Industry Working Group, 2012). Sixth, there are proven, high value markets for native forest timbers. Over 90% of surveyed native forest sawmills nationally were positive about the outlook for demand for their products, with this high market standing reflected by the average price of sawn native forest hardwood being $1254/m^3, while the average price of sawn Australian plantation softwood is about $391/m^3 (Downham et al., 2019). The native forest milling sector of Australia does not need to operate at the same scale as the softwood sector to be internationally competitive (URS Australia, 2012).

In developed and developing countries, insecure and uncertain property rights to timber are major causal factors of high-grading, short harvest return intervals, limited investment in silviculture, biodiversity loss and ultimately socio-economic or political pressures for deforestation (Zhang, 2001; Fredericksen and Putz, 2003; Souza et al., 2012; Petrokofsky et al., 2015b; Putz and Ruslandi, 2015; Simmons et al., 2018b). A considerable challenge to timber production through land sharing in QLD is overcoming sovereign risk. Changes in land management laws have been closely aligned to changes in government (Reside et al., 2017), resulting in 40 amendments to vegetation management laws since 2000 (AgForce, 2021) and landholders exhibiting a severe lack of trust in the QLD government (Brown et al., 2021). Private native forestry is not prohibited, but the incremental legislative restrictions periodically reduce the area that can be managed for timber production and change allowable silvicultural practices, which raise forest management costs and lower potential harvest revenues. This has discouraged forest management and caused periods of expedited planned and unplanned clearing to generate less risky income streams from cattle or cropping (Queensland CRA/RFA Steering Committee, 1998a; Bureau of Rural Sciences, 2004; Simmons et al., 2018a).

In a national survey of wood processing facilities, 47% of native forest hardwood sawmills identified resource insecurity as the main issue influencing their future investment decisions (Downham et al., 2019), but in QLD this proportion is 82% (Francis et al., 2020). Resource insecurity substantially increases business risk, which reduces investment, industry competitiveness and resilience. Reduced industry competitiveness lowers stumpage prices, which further reduces the financial viability of landholder investments in forest management. Therefore, resource insecurity can establish a reinforcing downward spiral for the industry. Certainty of harvest rights will encourage long-term investments in sustainable forest management and increase investment throughout the timber value chain (Forest and Timber Industry Working Group, 2012; Matysek and Fisher, 2016; Dare et al., 2017; Downham et al., 2019). Further research is necessary to quantify the ecological and economic trade-offs associated with securing domestic timber production under land sharing and land sparing policies.

6. Resourcing domestic forest management through land sharing and sparing

Protected area targets are prominent in international conservation commitments, such as Target 3 in the Kunming–Montreal Global Biodiversity Framework for the Convention on Biological Diversity (UNEP, 2022), and these are consistent with strict conservation reserves established through land sparing. The reality in Australia and internationally is that strict conservation areas are unlikely to be sufficient for preserving biodiversity and carbon due to their limited area, failure to adequately capture all forest types or successional stages, poor connectivity and insufficient funding to protect wildlife habitat, manage weeds and feral animals, and implement ecologically appropriate fire regimes (Brown, 1996; McAlpine et al., 2005; Wilkinson, 2006; Taylor et al., 2011; Craigie et al., 2014; Adams et al., 2019; AFPA, 2020; Giustafsson et al., 2020; Rossiter et al., 2020; Sheppard, 2021). Global studies suggest only 20% to 50% of the world's protected areas are effectively managed, with under-resourcing being the primary reason for poor management (Watson et al., 2014). In Australia, the expansion of native forests within National Parks and other conservation reserves from 8.4 to 22 M ha since 1990 (AFPA, 2020) has been accompanied by a progressive loss of forest management and research capacity, with the field workforces of state government land management agencies declining by about 50% to 67% over the same time period (Queensland CRA/RFA Steering Committee, 1998b; McAlpine et al., 2005; Whiteman et al., 2015; Queensland Department of Agriculture and Fisheries, 2016; Kanowski, 2017; NSW DPI Forestry, 2018; Morgan et al., 2020).

Under-resourcing can lead to both catastrophic and more gradual forms of habitat degradation and poor biodiversity conservation outcomes (Brown, 1996; McAlpine et al., 2005; Wilkinson, 2006; Taylor et al., 2011; Craigie et al., 2014; Balmford et al., 2018b; Adams et al., 2019; Giustafsson et al., 2020; Rossiter et al., 2020; Adams et al., 2021; Graham et al., 2021; Sheppard, 2021). Given limited resources for conservation, there is a need for evidence-based methods to expend resources efficiently by using principles of ecology and economics (Murdoch et al., 2007; Possingham et al., 2015; Ando and Langpap, 2018; Adams et al., 2019; Kuempel et al., 2020). A critical question is, to what extent should resources be allocated to expanding the conservation estate (i.e. increasing land sparing) versus improving management of existing protected areas to an acceptable standard, and complementing the conservation estate with land sharing? Improving management of existing conservation areas is often a better first investment (Kearney et al., 2018; Adams et al., 2019).

For decades, the operational funding level for QLD's publicly-owned protected area estate ($16/ha in 2017–18) has been recognised as very low in comparison to other Australian states and internationally, and as inadequate for their long-term effective management (Tom Fenwick and Assoc. PTY LTD, 2000; McAlpine et al., 2005; Queensland Treasury Corporation, 2018). Nature Refuges, a voluntary conservation program for private landholders in QLD, which accounts for over 4.4 million hectares in the state, has received average annual support from the QLD Government of $0.25/ha (Allen et al., 2018; Our Living Outback, 2019). The QLD Parks and Wildlife Service annual prescribed fire targets for ecological benefits and wildfire risk reduction are often not achieved because of a lack of resources, in addition to unfavourable burning conditions (Eliott et al., 2020). Indeed, Australia has a long tradition of holding inquiries following major wildfire events that recommend greater government resourcing of fuel management, followed by failure to implement due to a lack of resources and other constraints (Kanowski et al., 2005; McCaw, 2013; Ximenes et al., 2017; AFPA, 2020; Groves, 2021; Keenan et al., 2021; van Oldenborgh et al., 2021).

Severe resource shortages have led to the adoption by default of a ‘benign neglect’ approach to conservation in QLD (McAlpine et al., 2005), which appears to be contributing to declining state-wide biodiversity conservation outcomes (Queensland Treasury Corporation, 2018). In 2018, the QLD Government's approach to conserving and managing threatened species had been evaluated as lacking a strategy or framework and being unlikely to effectively conserve and recover many threatened species (Allen et al., 2018; Queensland Audit Office, 2018; Queensland Treasury Corporation, 2018). Limited improvement had been achieved by 2023 (Queensland Audit Office, 2023). To fund necessary upgrades in management of existing National Parks and private Nature Refuges, the Wilderness Society et al. (2019) and National Parks Association of QLD Inc. et al. (2020) recommended the annual operating budget of the QLD Parks and Wildlife Service be more than doubled from $111 million in 2017–18 (Queensland Audit Office, 2018) to $246 million.

Long-term under-resourcing of land sparing highlights the need to consider opportunities for land sharing to improve native forest management through providing income streams from the sale of logs and by mobilising private sector resources. As business managers, rural landowners have financial incentives to respond to government policy and market signals to actively manage forest in ways that will benefit biodiversity conservation, including through prescribed fire, control of invasive species and maintenance of important infrastructure such as fire breaks, at levels rarely possible in the publicly-owned conservation estate (Tucker and Wormington, 2011; Petrokofsky et al., 2015a; Evans, 2018). Forest policy that facilitates land sharing could substantially improve fire management at the landscape-scale by encouraging private sector investment in native forest silviculture, which can reduce the extent of wildfires by providing improved access, fire breaks, heterogeneity in fuel composition and structure, and through maintaining skills and capacity to manage prescribed fires and wildfires in difficult forest terrain (Stephens, 2010; AFPA, 2020; IFA / AFG Board, 2020; Tolhurst and Vanclay, 2021). The Australian red meat sector has a goal to achieve carbon neutrality, and improved native forest management and reforestation of between 5 million ha and 12 million ha of grazing land on these working landscapes are part of the industry's strategy (Mayberry et al., 2019). Forest policy that is supportive of land sharing is more likely to facilitate private sector investment to achieve this goal than land sparing. Forest policy design can be improved by better accounting for the implications of land sharing and sparing policies on resourcing of forest management and the associated ecological and economic trade-offs.

7. Effects of land sharing and sparing on wildfire risk in Australia

Wildfire is a major socio-economic hazard in Australia (Venn and Quiggin, 2017); nevertheless, there is scarce Australian literature on whether forestry (land sharing) affects wildfire risk. Papers have focussed on temperate forests managed under clearfelling regimes, are based on limited empirical evidence, and are conflicting in their findings (Keenan et al., 2021). Lindenmayer et al. (2009, 2011, 2020) proposed that harvesting in temperate mountain ash (*Eucalyptus. regnans*) forests of VIC has resulted in drier forests with structures that tend to be more fire-prone. Similarly, Furlaud et al. (2021a, 2021b) argued harvested wet sclerophyll forests of Tasmania are more vulnerable to a ‘landscape trap’ effect, where intensive disturbance creates large areas of regrowth stands with increased risk of high severity wildfire. Others have argued forest flammability can be explained in terms of stand structure and fuel accumulation rather than a dichotomy of regrowth stands being highly flammable, and mature stands not being highly flammable (Price and Bradstock, 2012; Attiwill et al., 2014; Adams et al., 2020). In QLD, NSW and VIC, analyses of the impact of the 2019–20 Black Summer Bushfires were not supportive of an argument that forestry makes forests more fire-prone or facilitated higher severity wildfire (Davey and Sarre, 2020; Bowman et al., 2021a; Bowman et al., 2021b; Natural Resources Commission, 2021).

Drought conditions are important for establishment of mega-fires (large, high-impact wildfires), but their potential appears to be greatest where historically diverse landscape mosaics have been lost, such as in many eucalypt forests of Australia (Williams, 2013). There is considerable evidence that forestry landscapes in Australia historically had both larger field workforces and more active fuel management programs than conservation areas, and had much smaller proportions of their estates burned by severe wildfire annually than conservation areas (Jurskis et al., 2003; AFAC, 2015; Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee, 2018). Land use, land use change and forestry data from the Australian Greenhouse Emissions Information System administered by the Commonwealth Department of Environment and Energy show a correlation between increasing wildfire burned area and decreasing prescribed fire burned area over the period 1990 to 2017 (Ximenes et al., 2017; AFPA, 2020). While correlation is not causation, numerous Australian and international studies have found mechanical fuel reduction treatments and prescribed fire improves the resilience of landscapes to wildfire, reduces the risk of catastrophic wildfire, increases carbon sequestration and benefits biodiversity conservation (Stephens et al., 2012; Burrows and McCaw, 2013; Florec et al., 2013; McCaw, 2013; United States Department of Agriculture, 2015; Ximenes et al., 2017; Keenan et al., 2021; Lukpat, 2022).

Climate change is increasing the risk of uncharacteristically severe wildfire in QLD (Hughes and Alexander, 2016; Canadell et al., 2021; van Oldenborgh et al., 2021), and there is an urgent need for more active forest management through forest thinning and prescribed fire to return forests to their historically more fire-resilient ecological condition (Ximenes et al., 2017; AFPA, 2020; Morgan et al., 2020; Jackson et al., 2021). Volkova et al. (2017) found mechanical thinning in VIC alpine ash (*E. delegatensis*) forests reduced wildfire severity and increased fire survival of trees. A combination of low severity fire and forest management techniques that mimic low severity fire, such as irregular shelterwood harvesting, dispersed retention harvesting and variable density thinning, has been suggested to create more fire resilient landscapes in Tasmania (Furlaud et al., 2021a; Furlaud et al., 2021b). Strong consideration also needs to be given to the potential for a greater role of cultural burning in management of Australia's native forests (Williamson, 2022). Bowman et al. (2020) argued the need for more landscape-scale experiments in Australia, along with improved understanding of the carbon trade-offs associated with alternative fuel management strategies. Implications of land sharing and sparing practices on wildfire management and risk should inform forest policy.

8. Domestic biodiversity conservation trade-offs associated with land sharing

While recognising that natural forest areas permanently protected from anthropogenic disturbances are essential, especially to conserve species dependent on old-growth forests, numerous international studies in tropical, subtropical and temperate forests have concluded that forest biodiversity conservation can be enhanced by a mosaic of selectively harvested and unharvested areas when appropriate silviculture is employed and forests are protected from illegal and planned land clearing (Verschuyl et al., 2011; Burivalova et al., 2014; Edwards et al., 2014a; Mori and Kitagawa, 2014; Biber et al., 2015; Dieler et al., 2017; Schall et al., 2018; Runting et al., 2019). There is no international evidence that selection harvesting has caused the extinction of any flora or fauna (Koh and Gardner, 2010). This section reviews evidence of the effects of land sharing with selection harvesting on biodiversity conservation in Australia. It commences with an evaluation of timber harvesting as a historic cause and contemporary threat of species extinction. Then the opportunity for land sharing to complement land sparing to enhance biodiversity conservation efforts in Queensland is outlined. This is supported by a review of literature on the impacts of selection silvicultural systems on Queensland's forest flora and fauna, with greater detail provided in Appendix A.

8.1. Evidence of forestry as a historic cause and contemporary threat of extinction in Australia

The 100 Australian species formally listed as extinct (or extinct in the wild) since European colonisation in 1788 make Australia responsible for about 6% to 10% of the world's post-1500 recognised extinctions (Woinarski et al., 2019). On the list are one protist, 38 vascular plants, ten invertebrates, one fish, four frogs, three reptiles, nine birds and 34 mammals. For most species, causality is not well established, and Woinarski et al. (2019) made an assessment of the likely relative contribution of factors for each extinction. There are four extinct Australian species for which timber harvesting may have been a causal factor. Those species, along with the relative contribution of timber harvesting to their extinction are: *Aplonis fusca* (Tasman starling, 3.3%); *Nestor productus* (Norfolk Island kaka, 1.7%); *Psephotellus pulcherrimus* (paradise parrot, 3.3%); and *Pteropus brunneus* (dusky flying-fox, 10%). This suggests it is improbable that an Australian species has become extinct due to timber harvesting.

Ward et al. (2021) engaged taxonomic experts in generating taxon-specific threat and threat impact information to consistently apply the IUCN Threat Classification Scheme and Threat Impact Scoring System to summarise data on recognized threatening processes affecting all 1795 nationally listed threatened taxa in Australia. Eight broad-level threat categories and 51 subcategory threats were applied, and a total of 4877 unique taxon-threat combinations identified. The three most frequently listed broad-level threats were habitat loss, fragmentation, and degradation (1210 taxa), invasive species and diseases (966 taxa), and adverse fire regimes (683 taxa). Top-ten subcategory threats include invasive weeds (565 taxa), agriculture and aquaculture (411 taxa), other habitat loss, fragmentation and degradation (398 taxa), transportation and service corridors (324 taxa), invasive predator (276 taxa), urban development (242 taxa), suppression in fire frequency or intensity (227 taxa), invasive ungulate (178 taxa), and disease (159 taxa). Outside the top-ten, the subcategory threat 'human intrusion' accounts for recreational activities such as bushwalking, dog walking, and horse riding, which was found to threaten 110 species nationwide. Forestry was the 25th most important subcategory threat, with a total of 43 listed species impacted nationally, of which 14 species occur in QLD and are listed in Table 1. This is 1.3% of the 1034 listed threatened species in Queensland (Queensland Audit Office, 2023). The majority of Australian threatened taxa are affected by multiple threats. For example, *Petauroides volans* (greater glider), has four subcategory threat listings, of which forestry has the least impact. The forestry threat for *Lathamus discolor* (swift parrot) is in this species' breeding grounds in Tasmania. The *Macrozamia* species listed in Table 1 have limited distribution in QLD, and the birds listed at the bottom of Table 1 prefer forests that are not targeted by the timber industry.

The minor contribution of forestry as a threatening process for nationally listed threatened taxa in Australia is consistent with other Australian studies that have highlighted invasive species, modified fire regimes, agriculture, urban development, and tourism and recreation as being far more important threatening processes (Braithwaite, 2004; Burgman et al., 2007; Rankin et al., 2015; Woinarski et al., 2017; Davey, 2018b; Kearney et al., 2019; Murphy et al., 2019). Unlike other threatening processes, there are substantial opportunities to modify forestry practices (e.g. retention of habitat trees and stream zone buffers) to accommodate the conservation of particular threatened species over space and time (Davey, 2018b; Slade and Law, 2018; Munks et al., 2020). In southern QLD, the greatest threats to biodiversity conservation have been identified as land clearing for urban development and agriculture, inappropriate fire regimes, and invasive species (McAlpine et al., 2005; Evans et al., 2011).

8.2. The opportunity for land sharing and sparing to provide complementary benefits for flora and fauna conservation

Patch-based conservation approaches that focus on one or a small set of important species have been the norm and these tend to assume an equilibrium state for natural ecosystems (Lindenmayer et al., 2008). While this approach is likely to be required for some species, it can fail if the surrounding landscape continues to degrade, will always involve substantial trade-offs with the conservation of other species, and is complicated and probably impossible to implement at a landscape level (Lindenmayer and Franklin, 2002; McAlpine et al., 2002; Lunney and Matthews, 2004; McAlpine et al., 2005; Lindenmayer et al., 2008). Forest ecologists recognise the need for conservation strategies to consider mosaics, landscapes and broader regions, with Lindenmayer et al. (2008) and Sayer et al. (2013) providing guidance on principles for conservation at the landscape-scale, including:

- recognising that disturbances can be valuable for ecosystems and biodiversity;
- planning to accommodate successional dynamics, spatial and temporal mosaics, localised colonisation and extinction processes, and likely range shifts associated with climate change;
- adopting an experimental framework to 'limit the risk of making the same mistake everywhere'; and

Table 1
Species in QLD listed under Australia's Environmental Protection and Biodiversity Conservation (EPBC) Act (1999) as threatened by forestry.

Species and common name	Group	EPBC Act status [a]	Subcategory threat	Impact score [b]
Hirundapus caudacutus Eastern white-throated needletail (Australia)	Birds	VU	**Forestry**	**8 (high)**
			Herbicides and pesticides	5 (low)
			Collision (wind turbines)	3 (low)
			Transportation and service corridors (utility and service lines)	3 (low)
Lathamus discolor Swift parrot	Birds	CR	**Forestry**	**8 (high)**
			Agriculture and aquaculture	7 (med)
			Increased frequency/ severity of drought	7 (med)
			Collision (vehicles and wind turbines)	5 (low)
			Disease	5 (low)
			Invasive species (bird and invertebrate)	5 (low)
			Problematic native species	5 (low)
			Increase in fire frequency/intensity	4 (low)
			Urban and commercial development	3 (low)
Anthochaera phrygia Regent honeyeater	Birds	CR	Agriculture and aquaculture	8 (high)
			Genetic introgression/ hybridisation	8 (high)
			Forestry	**7 (med)**
			Increased frequency/ severity of drought	7 (med)
			Invasive species (rabbit)	6 (med)
			Problematic native species	6 (med)
			Urban and commercial development	6 (med)
			Habitat shifting and alteration (climate change)	4 (low)
Bettongia tropica Northern bettong	Mammals	EN	Habitat shifting and alteration (climate change)	7 (med)
			Other change in fire regime	7 (med)
			Agriculture and aquaculture	6 (med)
			Forestry	**6 (med)**
			Invasive predators (cats and foxes)	6 (med)
			Invasive ungulate	6 (med)
			Genetic introgression/ hybridisation	5 (low)
Petauroides volans Greater glider	Mammals	VU	Agriculture and aquaculture	7 (med)
			Habitat shifting and alteration (climate change)	7 (med)
			Other change in fire regime	7 (med)
			Forestry	**6 (med)**
Petaurus australis Wet Tropics subspecies Yellow-bellied glider	Mammals	VU	Agriculture and aquaculture	7 (med)
			Forestry	**6 (med)**
			Invasive predator (cats)	6 (med)
			Other change in fire regime	6 (med)
Phyllodes imperialis smithersi Pink underwing moth	Invertebrate	EN	Agriculture and aquaculture	6 (med)
			Forestry	**6 (med)**
			Invasive species (weeds)	6 (med)
			Light pollution	5 (low)
			Urban and commercial development	5 (low)
Tylophora woollsii	Plants	EN	Invasive weed	7 (med)
			Inappropriate disturbance regimes	7 (med)
			Other natural system modification	7 (med)
			Forestry	**6 (med)**
			Transportation and service corridors	5 (low)
Owenia cepiodora Onionwood, bog onion, onion cedar	Plants	VU	Invasive weed	6 (med)
			Forestry	**5 (low)**
Macrozamia machinii	Plants	VU	Direct harvest	5 (low)
			Forestry	**4 (low)**
Macrozamia conferta	Plants	VU	Fire and fire suppression	3 (low)
			Forestry	**3 (low)**
Macrozamia parcifolia	Plants	VU	Fire and fire suppression	3 (low)
			Forestry	**3 (low)**
Atrichornis rufescens ferrari Southern rufous scrub-bird	Birds	EN	Increase in fire frequency/intensity	8 (high)
			Increased frequency/ severity of drought	7 (med)
			Agriculture and aquaculture	1 (neg)
			Forestry	**1 (neg)**
Dasyornis brachypterus brachypterus Southern eastern bristlebird	Birds	EN	Increase in fire frequency/intensity	8 (high)
			Increased frequency/ severity of drought	7 (med)
			Invasive predator (cat and fox)	5 (low)
			Invasive weed	5 (low)
			Agriculture and aquaculture	1 (neg)
			Forestry	**1 (neg)**
			Human intrusion	1 (neg)
			Urban and commercial development	1 (neg)

Notes: a. EPBC Act threatened species status categories are: CR, critically endangered; EN, endangered; and VU, vulnerable.
b. Taxonomic expert assignment of the IUCN Threat Impact Scoring System. Threats to a taxon are scored on the basis of timing of the threat (i.e. past, ongoing or future), the scope of the threat (defined as the proportion of the whole population affected), and the severity of the threat (defined as the overall declines in population of the taxon). The maximum possible impact score is 9. Impact scores under 2 are negligible impact, 2 to 5 are low impact, 6 to 7 are medium impact, and 8 to 9 are high impact.
Source: Ward et al. (2021).

- creating human disturbance regimes that are similar to natural regimes.

International forest restoration literature suggests forestry silvicultural practices can contribute to biodiversity conservation through facilitating heterogeneity at the landscape-scale by managing the (a) harvest and silvicultural treatment intensity, (b) retained structural elements, and (c) spatial configuration of forests with different times since disturbance at multiple scales in the landscape (Liu and Taylor, 2002; Millar et al., 2007; Stanturf et al., 2014; Leitão et al., 2022). In international agricultural and forestry settings, the triad approach (policy B in Fig. 1) at the landscape scale has frequently been found to generate particularly high regional biodiversity values, because different suites of species benefit from extensive, intensive and conservation land management practices (Finch et al., 2019; Runting et al., 2019; Finch et al., 2020; Betts et al., 2021; Sidemo-Holm et al., 2021). Lindenmayer et al. (2006) argued that landscape-scale spatial and temporal variation in conditions is also a useful risk-spread strategy, because there is a dearth of information about how most species respond to disturbances such as timber harvesting, wildfire and climate change. While there is debate about the extent to which silviculture can mimic natural disturbance processes, many forest ecologists recommend development of creative silviculture to improve the climate resilience, ecological health, biodiversity conservation, water yield and carbon sequestration potential of forests (Ashton and Kelty, 2018; Gustafson et al., 2020; Korb et al., 2020; Palik et al., 2020; Thom and Keeton, 2020; Nevins et al., 2021; Ren et al., 2021; Thom et al., 2021).

In the Australian context, strong arguments have been made in support of adopting a landscape-scale approach to enhancing ecological, structural and species diversity through diverse forest management practices achieved via a mixture of fire management and silvicultural interventions within areas managed for land sharing and land sparing (Attiwill, 1994; Florence, 1996; Wilkinson, 2006; Holland and Bennett, 2007; Eyre et al., 2015a; Gonsalves et al., 2018b; Kearney et al., 2018; Law et al., 2019; AFPA, 2020; Baker et al., 2020b; Jackson et al., 2021; Saunders et al., 2021). The landscape-scale approach makes it feasible to aim to avoid local extinctions of all species, while accepting that populations of individual species will fluctuate throughout the landscape over time in response to temporally dynamic disturbances (McIlroy, 1978; Loyn and McAlpine, 2001; Smyth et al., 2002).

Evaluation of the contribution that land sharing can make to biodiversity conservation in QLD requires an understanding of the sensitivity of species to selection timber harvesting. The selection harvesting regimes permitted in QLD's native forests affect forest structure, which provides temporary advantage or disadvantage for some species of flora and fauna. Little had been published on this subject for QLD's eucalypt forests prior to the South East QLD Forest Agreement (Kavanagh et al., 2004), and following implementation of the agreement there were drastic cuts to forest research and management budgets (McAlpine et al., 2005). Consequently, there is limited and dated literature on forestry effects on biodiversity in QLD. In contrast, substantial levels of research have been performed in northern NSW, which is ecologically similar to southeast QLD. The review of literature on the effects of selection harvesting on QLD's flora and fauna in Appendix A draws heavily upon that research and is summarised below.

The majority of floristic diversity in Australia's eucalypt forests is found in the understorey, and there is a large body of evidence that the conservation of Australian forest flora is threatened by a lack of disturbance (Jurskis, 2005; Turner et al., 2008; Close et al., 2009; Close et al., 2011; Horton et al., 2013; Steinbauer et al., 2015; Baker et al., 2020a). The majority of QLD's threatened species are plants (Queensland Government, 2021). In QLD, high stocking of suppressed eucalypt trees persisting below the canopy, sclerophyll shrubs and rainforest invasion are widely reported in fire-excluded sclerophyll forests, recognised as a major threat to the conservation of floristic biodiversity, and implicated in premature tree decline (Nicholson, 1999; MBAC Consulting Pty Ltd, 2003a, 2003b; Ryan and Taylor, 2006; Chapman and Kofron, 2010; Stanton et al., 2014; Krishnan et al., 2019). In this context, forestry practices including thinning, prescribed fire and harvesting, appear to have neutral to positive effects on the conservation of Australian floristic diversity (Penman et al., 2008; Lewis and Debuse, 2012; Jones et al., 2015; Gonsalves et al., 2018b; Brown et al., 2019).

In a comprehensive assessment of the impacts of timber harvesting on forest fauna in northern NSW, Kavanagh and Stanton (2005) found mammals were the taxonomic group containing the largest proportion of species disadvantaged, compared to those favoured by harvesting, although the majority were not significantly affected. The six key threats to QLD's koala (*Phascolarctos cinereus*) population are well-known and do not include forestry (McAlpine et al., 2006; McAlpine et al., 2015; Rhodes et al., 2017). There is substantial evidence that koala populations are highly resilient to disturbance by selection harvesting (Natural Resources Commission, 2021; Law et al., 2021; 2022a; 2022b), and additional detail is provided in Appendix A. The conservation of hollow-dependent arboreal mammals can be severely impacted by the removal of large trees with hollows (habitat trees) (Eyre et al., 2010). Nevertheless, populations of arboreal hollow-dependent mammals have remained high in Kioloa State Forest (now Murramarang National Park) and McPherson State Forest, NSW, and 11 State Forests in southeast QLD after long histories of harvesting (Florence, 1996; Eyre and Smith, 1997; Wormington et al., 2002; Law et al., 2013). Existing QLD forestry codes of practice (Department of Natural Resources and Mines, 2014) are compliant with empirical evidence-based habitat tree retention recommendations to conserve arboreal mammal species richness and abundance, including for the yellow-bellied glider (*Petaurus australis*) and greater glider (*Petauroides volans*) (Wormington et al., 2002; Eyre, 2005; Eyre, 2006).

Australia's diverse ground-dwelling forest mammals have different and often mutually exclusive forest understorey habitat requirements. Managers of wet and dry sclerophyll forests in eastern Australia can sustain the ecosystem functions performed by ground-dwelling mammals by conserving a mosaic of structurally complex vegetation, as well as structural heterogeneity through horizontal patchiness of vegetation at the landscape-level (Holland and Bennett, 2007; Sukma et al., 2019). Harvesting, thinning and prescribed fire associated with selection silvicultural systems will produce structural complexity and heterogeneity across the landscape (Florence, 1996). Silvicultural treatments have been found to have neutral to positive effects on the conservation of Australia's ground-dwelling mammals (Wayne et al., 2011; Bain et al., 2016; Gonsalves et al., 2018b).

Throughout Australia, the majority of bird species are not affected by native forest harvesting (Kavanagh et al., 1995; Calver and Dell, 1998; Maron and Kennedy, 2007; Abbott et al., 2011; Barnes et al., 2015; Lindenmayer et al., 2019). Out of 129 bird species in northern NSW with sufficient data for analysis, 83 species were not statistically significantly affected by native forest harvesting, 26 species were temporarily advantaged by harvesting and 20 species were temporarily disadvantaged (Kavanagh and Stanton, 2005). In cypress-eucalypt woodland in QLD and NSW, bird species richness tends to be significantly higher in selectively harvested areas than unharvested areas, although the abundances of individual species may vary (Eyre et al., 2015a; Murphy, 2020). Owl species are well-distributed throughout timber production forests in NSW and have been shown to respond to harvesting and wildfire disturbance by recolonising areas as forest regeneration proceeds (Kavanagh et al., 1995; NSW Department of Environment and Conservation, 2006).

Native forest harvesting and thinning practices have neutral to positive effects on reptile species richness and abundance in QLD, NSW and WA, relative to conservation or long unharvested forests (Goodall et al., 2004; Wayne et al., 2011; Eyre et al., 2015a; Gonsalves et al., 2018b). Kavanagh and Stanton (2005) examined the impact of selection harvesting on 41 reptile species in northern NSW, finding 33 species were not significantly affected by harvesting, four species were significantly favoured, and four species were significantly disadvantaged. Lemckert (1999) examined the effect of selection harvesting on the species richness and abundance of breeding individuals for 29 frog species at 212 sites in the Dorrigo Management Area of northern NSW, finding that species richness was significantly positively related to the proportion of harvested forest, although the abundance of three species was temporarily reduced in harvested areas. Kavanagh and Stanton (2005) found one frog species was negatively affected by selection harvesting in north east NSW.

The literature review on QLD's flora and fauna presented in Appendix A and summarised above suggests that heterogenous landscapes are necessary to conserve QLD's full suite of biodiversity, and that the distribution and abundance of the majority of Queensland's flora and fauna are not substantially affected by selection harvesting. Selection silvicultural systems in QLD's native forests can: (a) restore wildlife habitat (Barr et al., 2011; Pike et al., 2011; Sitters et al., 2016; Gonsalves et al., 2018a; Gonsalves et al., 2018b); (b) have an important role in achieving the regular disturbance necessary to promote and conserve floristic diversity (StClair, 2010; Baker et al., 2020a); (c) improve the resilience of large trees (including habitat trees) to climate change and wildfire (Bowman et al., 2014; Prior and Bowman, 2014; Bennett et al., 2015); (d) accelerate the development of many structural and composition components of old-growth eucalypt forests (including habitat trees) (Jurskis, 2000; Bauhus et al., 2009; Horner et al., 2010; McLean et al., 2015; Brown et al., 2019); and (e) promote and maintain the natural uneven-aged structure of these forests (Florence, 1996). Further research into the positive and negative impacts of selection harvesting on species of concern in QLD is warranted to investigate opportunities for land sharing to complement land sparing to improve biodiversity conservation outcomes in QLD, as well as internationally through reducing consumer demand for imported substitute timber.

9. A call to research to quantify and evaluate the ecological and economic trade-offs associated with land sharing and sparing

The review of ecological and economic trade-offs associated with land sharing and sparing has highlighted the complex decision-space of forest policy-makers. Development of ecologically sustainable and socio-economically efficient native forest policy requires an understanding of how policy decisions in QLD impact global efforts to conserve biodiversity and reduce carbon emissions. Policy-makers must also consider the diverse habitat requirements of QLD's forest flora and fauna, and how land sharing and sparing management activities can be resourced from the public and private sectors to produce the landscape mosaics necessary for their conservation. It also requires an understanding of the economic factors that influence domestic private land use and determine the effectiveness of land sharing and sparing policies to secure domestic timber supplies. It appears that substantial ecological and economic benefits could be realised from improved domestic and international forest management if Australian policy-makers had access to tools that could support decision-making consistent with the intent of the National Forest Policy Statement (Commonwealth of Australia, 1992), which recognises the need for a sound scientific basis for sustainable forest management, efficient forest use, and provision of other social and conservation objectives. The land sharing–sparing framework is well-suited to the task, but application in QLD will require:

1. quantification of the ecological and economic trade-offs summarised in Sections 3 to 8 of this paper;
2. establishment of reference conditions against which ecological conditions under alternative forest management approaches can be evaluated; and
3. development of a spatially and temporally-explicit decision support tool that can organise the large datasets from (1) and (2) to explore and evaluate the ecological and economic performances of alternative landscape-scale forest management scenarios.

Data from empirical studies and predictive models are required to relate the abundance of large numbers of species, timber production and provision of other ecosystem services (e.g. carbon sequestration) with forest successional stages due to natural disturbances, conservation management and silviculture for timber production (Phalan et al., 2011; Betts et al., 2021). A research program to quantify biodiversity conservation–forestry trade-offs is required to inform decision-making in QLD, perhaps with an initial focus on the 14 threatened species believed to be impacted by forestry operations in the state. Where possible, longitudinal ecological studies that track forest stands subjected to alternative management regimes over time should be implemented, although space-for-time studies representing the successional spectra of ecological communities are likely to be more feasible due to research funding structures (Betts et al., 2021). Expert opinion may also be required to fill holes in knowledge gained from empirical studies (Runting et al., 2019). These data can be used to derive species density–timber yield functions over time, using methods similar to those described by Green et al. (2005) and Balmford et al. (2018b).

Some ecologists, including Phalan et al. (2011), do not consider economics in the land sharing–sparing framework. However, the reality is that society has scarce resources, and there are large costs (including opportunity costs) associated with effective conservation, extensive and intensive forest management strategies (Possingham et al., 2015; Tisdell, 2015; Sidemo-Holm et al., 2021). The literature review highlighted a need to develop several economic trade-off functions to support forest policy-making in QLD, including:

- international ecological footprint–timber yield functions to account for the global ecological opportunity cost of reduced domestic wood production, with studies such as Wiedmann et al. (2015) and Kitzes et al. (2017) providing potential frameworks for quantifying the footprint of imported goods;
- carbon sequestration–timber yield functions that adopt a LCA approach similar to the analyses performed by Ximenes et al. (2012, 2016) for northern NSW to comprehensively assess carbon sequestration associated with domestic native forest management, and the carbon emissions associated with utilisation of substitute non-wood and imported wood products;
- species density–conservation funding functions to account for potential improvements in biodiversity conservation in strict conservation areas with increased funding devoted to conservation management within existing protected areas versus new conservation areas (Possingham et al., 2015; Adams et al., 2019); and
- regional employment and income–timber yield functions, with Driml et al. (2020) and Francis et al. (2020, 2022) providing useful insights into the economic trade-offs between land sharing and land sparing in native forests.

One of the challenges to applying the land sharing–sparing framework is in establishing reference conditions against which alternative forest management approaches can be evaluated. Due to historic management, the current condition of the conservation estate may not provide appropriate reference conditions. The BioCondition framework developed by Eyre et al. (2015b) specifically for QLD ecosystems was applied by Lewis et al. (2020) to assess the impact of silviculture on several important ecological attributes in private native forests of southern QLD. The forests scored well (Lewis et al., 2020), although Thompson et al. (2006) asserted that these types of methods may not effectively discriminate between sound and poor forest management, and that they may be better suited to assess the ecological impacts of land clearing, rather than forestry.

Lindenmayer et al. (2006) warned that 'ecological short cuts' to evaluate sustainable forest management, such as indicator species and thresholds, have limited utility. Instead, they recommended general principles for managing forest biodiversity, including: maintenance of connectivity; maintenance of stand structural complexity; maintenance of landscape heterogeneity; the use of knowledge of natural disturbance regimes in natural forests to guide off-reserve forest management practices; and spatial and temporal variation in conditions as a risk-spread strategy. These principles are consistent with an alternative approach to setting reference conditions; aiming to mimic the historic range of variation (HRV) in the frequency, spatial pattern and extent of natural disturbance at the landscape scale (Greenberg and Collins, 2016). Given that native species evolved to tolerate such disturbance regimes, biodiversity is likely to be conserved if management practices approximate these (Landres et al., 1999; Venn and Calkin, 2008). Nevertheless, the HRV approach has been criticised because of insufficient data about historic disturbance regimes and because they may be inappropriate to guide management into the future with climate change (Betts et al., 2021). Further research is required to select appropriate methods to define reference conditions.

When ecological and economic trade-offs associated with land sharing and sparing have been empirically estimated, and reference conditions established, spatially-explicit land sharing–sparing scenarios can be defined, simulated over an ecologically appropriate time period, and evaluated with respect to their ecological and economic performances. In this context, decision support tools perform essential functions, including organising and retrieving large datasets, requiring explicit ('on the record') definitions of relationships between variables and providing a repeatable evaluation procedure, which together facilitate a deeper understanding of (and more effective communication about) the problem, highlight areas of consensus and disagreement, and help to build trust among stakeholders (Sayer et al., 2013). Internationally, forest managers have been extensive users of operations research (OR) to support the design and selection of management strategies in spatially and temporally complex ecological and economic systems (Venn, 2004; Ronnqvist et al., 2015; Beyer et al., 2016; Kaya et al., 2016). OR methods can provide insights into complex problems that human experts cannot, by generating many solutions via a series of parametric runs of the model and boosting the visioning of new and unexpected scenarios. Several recent applications of the land sharing–sparing framework for forest management have an OR platform, including Law *et al.* (2017b) and Runting et al. (2019). Geschke et al. (2018) applied land sharing–sparing with an OR platform in the context of compact versus sprawling Australian cities.

10. Conclusion

In many parts of the world, including Queensland (QLD), Australia, the ecological and economic realities that should inform native forest policy and management can become sidelined by politics, which threatens global action to conserve biodiversity and mitigate climate risk. By facilitating quantification of the timber production, biodiversity conservation and climate risk mitigation trade-offs associated with strict conservation, extensive forestry and intensive forestry, the land sharing–sparing framework can provide a transparent method to develop ecologically sustainable forest policy informed by science and economics. This paper introduced a modified conceptualisation of the framework to better reflect the role that trade in wood products plays in facilitating domestic land sparing by shifting the biodiversity and carbon footprint of consumption offshore. This paper also presented the first comprehensive review of the ecological and economic trade-offs between land sharing and sparing in QLD, finding that:

1. land sparing policies enacted by Australian states since the 1980s have coincided with a rapidly growing international ecological footprint of Australian consumers in forests of developing countries;
2. land sharing is likely to provide greater long-term climate risk mitigation benefits in QLD than land sparing coupled with substitution of domestic wood products for non-wood products and imported timbers;
3. land sharing can overcome many of the economic impediments to satisfying domestic timber demand through land sparing with timber plantations;
4. inadequate operational funding for conservation area management means increased land sparing is unlikely to effectively conserve and recover many threatened species;
5. there is no evidence that land sharing increases wildfire risk in QLD;
6. land sharing can mobilise private sector resources for domestic conservation and wildfire management activities;
7. conservation of the majority of native flora and fauna in QLD is not substantially affected or is enhanced by land sharing, while land sparing can benefit a comparatively small group of species that require long undisturbed forests; and
8. a mix of land sharing and land sparing (the triad policy B in Fig. 1) shows greatest promise to conserve the full suite of biodiversity in QLD by producing diverse ecological and structural conditions over space and time.

Given the ecological and economic realities of forest management in QLD, it is challenging to mount a strong argument in favour of increased land sparing in the state. However, for QLD to take full advantage of the benefits of land sharing for biodiversity conservation, and climate risk mitigation, sovereign risk must be addressed. Further research is justified to tackle gaps in knowledge, quantify the ecological and economic trade-offs between sharing and sparing, and explore opportunities to apply the sharing–sparing framework to inform evidence-based forest policy in QLD.

Declaration of Competing Interest

The author owns a hobby farm.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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