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ORIGINAL RESEARCH

Timber Production Opportunities from Private Native Forests in Southern Queensland

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Abstract
Historically, Queensland's private native forests have supplied between 40 and 70% of the hardwood resource to the state's primary processors. Hardwood timber production from state-owned native forests and plantations in Queensland has decreased substantially in recent decades, increasing the hardwood timber industry's reliance on private native forests. However, timber production opportunities from these forests are poorly understood. This study assessed the future wood supply capacity from private native forests in southern Queensland assuming alternative levels of landowner interest in management for timber production and willingness to invest in silvicultural treatment. Commercial and harvestable private native forests in southern Queensland were classified into six forest types and their spatial distributions were assessed. Potential growth rates for each forest type were estimated based on available literature and expert opinion, and their ability to supply logs to industry with and without silvicultural treatments was projected. Commercial and harvestable private native forests were found to cover an area of approximately 1.9 M ha in southern Queensland, of which spotted gum (693,000 ha) and ironbark (641,500 ha) forest types are most common. The private native forest estate is distributed over 17,665 landholdings (LotPlans), with 17% of these accounting for 66% of the commercial and harvestable resource. Most private native forests have not been actively managed for timber production and are in poor condition. Nevertheless, they presently have the potential to supply between about 150,000 and 250,000 m^3 of logs to industry per annum. Silvicultural treatments were found to have the potential to increase the mean annual increment of these forests by a factor of between two and four, indicating substantial opportunities to increase harvestable log volumes in the medium and long-term. Private native forests in southern Queensland could potentially more than compensate for the supply gap left by the declining area of state-owned native forests that are available for timber harvesting. Actual forest management performed and log volumes supplied to market will depend on the forest management decisions of thousands of individual landholders, which are influenced by their heterogeneous management objectives, the policy environment, perceptions of sovereign risk, timber markets and the long payback

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periods in forestry. An accommodating forest policy environment and landholder willingness to invest in forest management could maintain and potentially increase private hardwood log supply to industry, which would support farm income diversification and regional employment opportunities.

Keywords Non-industrial private forest · Forest policy · Mean annual increment · Silviculture · Log yield

Introduction

Non-industrial private forests are critical to the supply of raw timber to processing industries and final consumers. In the European Union, more than 60% of forests are privately owned, with these forests being of major importance to timber supplies (Sjølie et al. 2018; Haugen et al. 2016). In the United States, 60% of forests are privately owned (Butler et al. 2021). By ownership, 31% of Australia's 132 million hectares of native forests are in private tenure (Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee 2018). Queensland contains the largest proportion of native forest in Australia (Neumann et al. 2021), with 51.8 million hectares in total and 14.3 million hectares privately owned (Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee 2018). It is likely that the reliance on private native forests to supply future timber demands will increase internationally, with policy decisions in various countries resulting in limitations on timber harvesting from public forestlands (e.g. Haynes 2002), privatisation of previously state-owned forests (e.g. Weiß et al. 2017), or prioritising harvesting from private land (e.g. Petucco et al. 2015). The ability of these forests to supply future timber needs to industry depends largely on the forest management and investment decisions of private landowners (e.g., Joshi and Arano 2009; Altamash et al. 2020).

Native forests in southern Queensland contain a diverse suite of hardwood timber species, including spotted gum (*Corymbia citriodora* subsp. *variegata* and *citriodora*), blackbutt (*Eucalyptus pilularis*) and ironbark (*Eucalyptus fibrosa* and *Eucalyptus crebra*) which have excellent and unique structural and aesthetic qualities (Ryan and Taylor 2006). Common uses for these timbers include green-off-saw structural timber, dry flooring and decking, landscaping products and electricity distribution poles (Francis et al. 2020a). In accordance with the Vegetation Management Act (VMA) 1999, private native forest management in Queensland is currently regulated by the accepted development vegetation clearing code, *Managing a Native Forest Practice: A Self-Assessable Vegetation Clearing Guide* (Department of Natural Resources, Energy and Mines 2014), hereafter referred to as the 'Code'. Consistent with the Code, best practice in southern Queensland's eucalypt forests is a selection harvest approximately every 10–20 years followed by a silvicultural treatment (D. Menzies, GIS Officer, personal communication, 24 June 2021). This provides adequate time for commercial stems retained at the last harvest to grow substantially in diameter (typically 10–25 cm depending on species and site quality) and log volume, while still being frequent enough to release advanced growth from competition before these trees become growth restricted.

The management and processing of timber from state-owned and privately-owned native forests has sustained employment and income generation opportunities in many regional communities of subtropical eastern Australia for over a century (Carron 1985; Jay and Dillon 2016). Increased scrutiny of public forest management has resulted in substantial declines in log volume supplied from state-owned native forests since the 1990s (ABARES 2019; Venn 2023), and the hardwood timber industry has become increasingly dependent on private native forests to maintain log supply in Queensland (Queensland Department of Agriculture and Fisheries 2015; Leggate et al. 2017). Over the period 2004 to 2018, the proportion of logs supplied by private native forests fluctuated between about 40 and 70% of the total in Queensland (ABARES 2019), with a mean contribution of 54%. At the time of writing there are 61 hardwood sawmills in Queensland, with 40 of those located in southern Queensland. In 2017, it was estimated that the total throughput of logs at hardwood sawmills within southern Queensland was about 325,400 m^3, with approximately 195,800 m^3 (60%) coming from private native forests (Francis et al. 2020a).

As part of the 1999 South-East Queensland Forest Agreement (Queensland Government 1999), the state government committed to phasing out timber harvesting in South East Queensland (SEQ) state-owned forests by the end of 2024 (McAlpine et al. 2005).[1] The SEQ Forest Agreement committed the state to establish hardwood plantations to make up for reduced supply to the industry from state-owned native forests (Norman et al. 2004; McAlpine et al. 2005) and encourage increased timber production from private native forests. However, the plantation expansion has been insufficient, with plantations often established on marginal sites with lower growth rates than expected and, in many cases, plantations failed to successfully establish (Nolan et al. 2005; Matysek and Fisher 2016; Queensland Department of Agriculture and Fisheries 2020b). There is limited investment interest in establishing new plantations or replanting harvested hardwood plantations in Queensland (Matysek and Fisher 2016), and the hardwood timber industry is expected to become increasingly reliant on private native forests (Burgess and Catchpoole 2016).

Increased reliance on private native forests is concerning for the timber industry. Landholders in Queensland have been discouraged from investing in native forest management because of decades of uncertainty regarding future harvest rights (sovereign risk), long payback periods, wildfire risk, and mistrust of harvesting contractors, as well as a lack of awareness about forest management practices, timber markets, and the potential timber value of well-managed forest (Queensland CRA/

[1] In 2019, a variation to the SEQ Forests Agreement was announced to support timber industry jobs. Timber production will end in 61,700 ha of State Forests in the SEQ Regional Plan area on 31 December 2024 (Queensland Department of Agriculture and Fisheries 2020a). However, state-owned native timber production will continue in 324,200 ha of state-owned forests in the Eastern Hardwoods Region, through to 31 December 2026 (Queensland Department of Agriculture and Fisheries 2020a). It remains unclear whether timber production in the Eastern hardwoods will continue post 2026. Together, these areas comprise the most productive remaining state forests in southern Queensland.

RFA Steering Committee 1998; Emtage et al. 2001; Bureau of Rural Sciences 2004; Herbohn et al. 2005; Ryan and Taylor 2006; Dare et al. 2017; Venn 2020). Uncertain property rights have been empirically linked to increased rates of land clearing in Queensland (Simmons et al. 2018). Consequently, private native forests are in poor productive condition due to decades of 'high-grading' without follow-up silvicultural treatment to thin non-merchantable stems (Ryan and Taylor 2006; Jay and Dillon 2016), an issue that is also observed outside Australia (e.g. Damery 2007; Russell-Roy et al. 2014). Although high-grading can be financially beneficial for landholders in the short-term (Jay and Dillon 2016), this practice produces stands with limited potential for future timber production, and declining genetic and ecological value over time (Florence 1996). If landholders can be encouraged to better manage their native forests, silvicultural thinning treatments could greatly improve productivity by increasing the proportion and growth of trees with commercial boles, as well as increasing log quality and size (Burgess and Catchpoole 2016; Jay and Dillon 2016; Hu et al. 2020; Lewis et al. 2020a; Francis et al. 2020a). Currently, only a small proportion of private native forests are managed with silvicultural thinning.

Current standing timber volumes in private native forests vary by forest type and management history; however, there are no publicly available records about the latter. The most recent timber inventories of private native forests in the region were published in the early 2000s and suggested the standing volume of sawlogs and poles was about 5.6 M m^3 in SEQ (MBAC 2003a) and 3.2 M m^3 in the Western Hardwoods Region (WHR) (MBAC 2003b). SEQ is contained entirely within the study area for this analysis, as are the most productive forests in the WHR. Confidence in these previous estimates is limited by lack of inventory data and long-term monitoring programs (Ngugi et al. 2018).

Several papers have been published that assess landholder attitudes towards forest management. On cleared agricultural land in Australia, landholders perceive the environmental and conservation benefits of tree planting as most important, while timber production is rarely considered (Emtage et al. 2001; Herbohn et al. 2005; Cockfield 2008a). Landholder attitudes towards timber production from private native forests in Australia are comparatively less-well understood; however, it appears that private native forest owners are more interested in managing their forests for timber production. For example, Dare et al. (2017) indicated that landholders who cumulatively own 55% of the private native forests in northern New South Wales were managing their forests for timber production. Cameron et al. (2019) summarised a 2018 Private Forestry Service Queensland (PFSQ) survey that included responses from 142 landholders in southern Queensland, finding that 85% managed their properties for both timber production and grazing. Cockfield (2008b) found that landholders in the Darling Downs, Queensland, and the New England Tableland, New South Wales, were unlikely to invest in management of their native forests for timber production, citing concerns over sovereign risk and the low economic benefits of forest management for timber production. However, Cockfield (2008b) also indicated that landholders may consider managing their forests for timber if it could be shown that combined grazing and timber production resulted in a net increase in income. Landholder surveys in eastern Australia have also revealed that larger landholders are more likely to manage their forests for timber production, while smaller landholders are more interested in conservation (Cockfield 2008b; Dare et al. 2017). The international literature has revealed similar heterogeneity in landholder preferences for forest management, with larger and longer-term private landholders more likely to engage in timber harvesting (Norldund and Westin 2011; Lawrence and Dandy 2014; Butler et al. 2016; Saulnier et al. 2017; Kreye et al. 2019).

The objective of this paper was to assess future timber supply opportunities from private native forests in southern Queensland under different levels of landowner interest in management for timber production and willingness to invest in silviculture. This information can support decision making about Queensland forest policy. Assumptions made about the area and growth rates of private native forest that may be managed for timber production have been guided by spatial analysis, literature and expert opinion. The paper proceeds by describing methods to define commercial forest types, estimate harvestable areas consistent with legislation, and estimate commercial growth rates with and without silvicultural treatment. Estimates of the timber production potential of private native forests are then reported and policy implications discussed.

Study Area and Methods

The study area covers 20.5 M ha, extending from the Queensland—New South Wales border, north to Rockhampton, and west to Goondiwindi, Miles and Injune. This is based on an earlier private native forest project (Lewis et al. 2010), and represents the approximate extent of commercially productive hardwood forest in southern Queensland.

The harvestable private native forest areas, silvicultural treatments and selection harvesting modelled in this analysis are compliant with the Code at the time of writing (Department of Natural Resources, Energy and Mines 2014), and a summary of Code requirements relevant to this study follows. The VMA describes native forest in Queensland as ‘remnant regional ecosystems’ (Category B vegetation), ‘regrowth regional ecosystems’ (Category C or R vegetation), or ‘non-remnant’ (Category X vegetation) (Department of Environment and Resource Management 2010). The Code lists the regional ecosystems (REs) in which a native forest practice is permitted. At the time of analysis, these included three coastal wet sclerophyll native hardwood forest REs, 241 other native hardwood forest REs, four cypress forest REs, and 37 rainforest REs. Three permissible silvicultural regimes are described, viz. a rainforest selection harvesting regime, a coastal wet sclerophyll forest group-selection regime, and a selection harvesting regime for all other hardwood and cypress pine forests. Clear-felling is not permitted. A native forest practice is not permitted where the majority slope is greater than 45% or 25 degrees. The minimum number of retained trees and habitat trees per hectare is specified depending on forest type and annual rainfall. Protection measures to minimise processes that accelerate soil erosion, cause watercourse instability, or land slips are specified, including detailed requirements for the placement and management of snig tracks and landings. No harvesting or silvicultural treatments can occur within buffers around streams, the width of which depends on the mapped stream order.

Defining and Mapping Commercial Forest Types

The extent of potentially harvestable private native forest in Queensland was determined through mapping carried out by the Department of Environment and Science (DES) in 2017 using ArcGIS Version 10.4.1. Lewis (2020) detailed the DES mapping methodology, and only a summary is presented below.

Spatial datasets for REs, foliage projective cover (FPC) (FPC14, Statewide Landcover and Trees Study, SLATS), remnant mapping (remnant cover 2015), high value regrowth (HVR), and other woody vegetation that was not considered remnant or high-value regrowth were added to the study area. Areas with slope less than 25 degrees (to meet Code requirements) were identified by generating a raster dataset from a one second SRTM (Shuttle Radar Topography Mission, NASA) derived hydrological Digital Elevation Model (DEM-H, Version 1.0, 2011). The union of FPC of at least 30%, slope less than 25 degrees and REs where timber harvesting is allowed under the Code, with remnant cover, HVR, and other woody vegetation, produced a total harvestable forest cover layer. Freehold land was selected using the Queensland Cadastral DCDB layer and was intersected with the total harvestable forest cover layer to identify harvestable private native forest. It was assumed that landholdings (LotPlans) with harvestable native forest areas of less than 20 ha were unlikely to have sufficient timber resources to warrant harvesting operations, and these were excluded from further analysis. It is possible that a single property with a single owner could be made up of multiple LotPlans with land acquisition occurring over time.

Six forest types were defined by grouping the 19 commercial forest types recognised in the PFSQ classification (PFSQ, c2015). The PFSQ forest types comprise only REs that are harvestable under the Code, and where the dominant species include recognised commercial *Eucalyptus* or *Corymbia* species, *Lophostemon confertus* or *Syncarpia glomulifera*. The six forest types were determined by industry experts based on dominant commercial species, which also reflect potential productivity, appropriate silviculture and commercial timber values. An additional category, named 'other harvestable forests', was included to represent forest types that were viewed as non-commercial by industry, despite being harvestable under the Code.

The six commercial forest types defined in this study have been presented along with the dominant commercial species within each (Table 1). Further description of the forest types, including a listing of REs is presented in Appendix 4 of Lewis et al. (2020c). The ironbark forests are primarily in the drier, less fertile western and northern parts of the study area. This does not include the coastal ironbarks (such as *E. siderophloia* and *E. fibrosa* subsp. *fibrosa*) which often grow within the spotted gum or mixed hardwood forest types. These ironbark trees often exhibit reasonable growth rates (0.45–0.49 cm DBH per year) but represent only a component of the stand (Grimes and Pegg 1979). The mixed hardwood forest type was so

Table 1 Commercial forest types adopted for the study area

Forest type	Dominant commercial species
Moist tall	*Eucalyptus pilularis* (blackbutt), *E. grandis* (flooded gum), *E. saligna* (Sydney blue gum), *E. acmenoides* (white mahogany), *E. cloeziana* (Gympie messmate), *Syncarpia glomulifera* (turpentine)
Mixed hardwood	*E. propinqua* (grey gum), *E. siderophloia* (grey ironbark), *E. acmenoides* (white mahogany)
Spotted gum	*Corymbia citriodora* subsp. *variegata* and *citriodora* (spotted gum), *E. crebra* (narrow-leaved ironbark)
Blue gum	*E. tereticornis* (Queensland blue gum / forest red gum), *E. crebra* (narrow-leaved ironbark), *E. siderophloia* (grey ironbark)
Gum-topped box	*E. moluccana* (gum-topped box)
Ironbark	*E. fibrosa* (broad-leaved red ironbark), *E. crebra* (narrow-leaved ironbark), *E. decorticans* (gum-topped ironbark), *E. siderophloia* (grey ironbark)
Other harvestable forests	Commercial species absent or at a density too low for financially viable harvesting operations

named, because relative to the other forest types: (i) the most common commercial species on any hectare varies considerably throughout the study area; and (ii) the relative frequency of the most common commercially important canopy species on any given hectare is lower than in the other listed forest types. The dominant commercial species listed are the three most common in the mixed hardwood forest type throughout the study area, although additional commercial species can be locally abundant.

The extent and distribution of the six commercial forest types and the other harvestable forests type was mapped with ArcGIS version 10.5.1 by grouping REs that make up each forest type and intersecting these with the harvestable private native forest layer from DES.

The Code specifies that stream orders one and two with stable water features require no buffer, and stream orders 3 and 4 require 5 m buffers. Only the highest stream order (5) requires more than a 5 m buffer. The majority of remnant forest is in upper catchment areas with low order streams. PFSQ (D. Menzies, GIS Officer, personal communication, 15 June 2021) estimated that Code requirements for stream buffers in the North Burnett region within the study area reduced harvestable forest area by 1.4%. In this analysis, a conservative 5% reduction in area for stream buffers has been adopted.

Estimating Forest Growth Rates And Log Yields With and Without Silviculture

Plot data were collected in moist tall and spotted gum forest as part of the larger project (Lewis et al. 2020a). However, for the remaining four commercial forest types defined in this study, growth data were obtained from a review of literature. A meeting of native forest experts was organised where a summary of new data and the published literature was presented, and a consensus was reached on appropriate mean annual increment (MAI) estimates for each forest type with and without silviculture. Table 2 summarises the MAI estimates from the new data (Lewis et al. 2020a) and the literature presented to the native forest expert group.

This assessment has focused on volume increments as these can be directly related to timber products. However, it is noted that basal area increments are also reported in the literature (e.g. Neumann et al. 2021), and these show similar trends in terms of greater increments in wet forests and lower growth increments in woodland environments.

The MAIs reported in Queensland CRA/RFA Steering Committee (1997) and Queensland CRA/RFA Steering Committee (1998) were for compulsory (high quality) sawlogs and estimated on the basis of average stand conditions and management regimes on state land, a condition that Bureau of Rural Sciences (2004) asserted is not a plausible approximation of the condition of the resource on private land. Nevertheless, the estimates from Queensland CRA/RFA Steering Committee (1998) were described as reflecting what could be achieved in private native forest if silviculture was improved to the standards practiced within State Forests. By the mid to late 1970s, silvicultural thinning began to be phased out in State Forests and had stopped completely by the late 1980s (Ryan and Taylor 2006). Therefore, although the average productive condition of State Forests is better than private native forests, MAIs estimated from State Forest data are unlikely to fully capture the potential of periodic (approximately every 10 years) silvicultural treatments to increase the productivity of private native forest.

The MAI estimates by forest type in Bureau of Rural Sciences (2004) were intended to reflect actual growth rates in private native forests, but were based on modelling undertaken by DPI Forestry using plot data from State Forests. MAI estimates were provided for moist and dry forests for four product categories: (1) compulsory sawlogs; (2) optional sawlogs; (3) girders and poles; and (4) post, round and utility products. The MAI of all four product categories was estimated to be 0.8 m^3/ha/yr in moist forests and 0.33 m^3/ha/yr in dry forests. For consistency with MAI estimates from all other sources in Table 1, only the MAI for compulsory sawlogs, optional sawlogs and poles and girders are presented.

Lewis et al. (2010) summarised data on nine silvicultural treatment tree spacing experiments from five State Forest spotted gum forests within the study area. Data was available for between 20- and 33-years post-treatment. The MAI of total stem volumes across all nine treatment spacing trials ranged from 0.88 m^3/ha/yr with a standard error (SE) of $\pm$ 0.06 m^3/ha/yr to 1.44 (SE $\pm$ 0.06) m^3/ha/yr. In contrast, the mean MAI of 40 plots in adjacent long untreated spotted gum forest was 0.35 m^3/ha/yr.

Lewis et al. (2020a) used data from a total of 203 plots to assess growth rates of treated and untreated stands mostly dominated by spotted gum in the same study area as the present study. Most of these plots were located on private land (158) across 19 sites, and forty-five plots were located in State Forest. The private native forest plots were established between 2010 and 2014. Repeated measures occurred between 2010 and 2017. Average growth rates of merchantable timber volume in this assessment ranged from 0.35 (SE $\pm$ 0.05) m^3/ha/yr in unmanaged stands in State Forest to 1.67 (SE $\pm$ 0.17) m^3/ha/yr in silviculturally treated regrowth forest, with an average of 1.2 (SE $\pm$ 0.07) m^3/ha/yr across all silviculturally treated plots.

Table 2 Published estimates of MAI for native forests in southern Queensland

Forest Type	MAI by source and product (m^3/ha/yr)							
	Florence (1996)	Queensland CRA/RFA Steering Committee (1997)[a]	Queensland CRA/RFA Steering Committee (1998)[b]	Bureau of Rural Sciences (2004)[c]			Lewis et al. (2010)	Lewis et al. (2020a)
				Compulsory sawlog	Optional sawlog	Girders and poles		
Wet forest	0.90 to 2.40	0.50 to 5.00	0.44	0.19	0.07	0.02		
Mixed hardwood	0.20 to 0.50							
Moist dry forest			0.18					
Dry forest		0.20 to 0.40		0.11	0.03	0.01		
Spotted gum							0.35 to 1.44	0.35 to 1.67
Woodland			0.15					

[a]These estimates are broad ranges of commonly observed MAIs in Crown native forests according to Department of Primary Industries – Forestry experts

[b]These estimates are the weighted (by area of each productivity class) average MAI for each forest type, where the average MAIs for high, medium and low productivity classes were essentially identical for all forest types, and estimated at 1.26, 0.45, and 0.05 m^3/ha/yr, respectively. A definition of woodland was not provided in the source paper. However, in Australia, a woodland is typically defined as an area with <30% canopy cover.

[c]Wet forests (described as moist forests) were defined as broad vegetation groups 2 and 2a (wet tall open forests dominated by *E. saligna, E. grandis, Lophestemon confertus* and *E. laevopinea*) 3 (moist open forest to tall open forest dominated by *E. pilularis*), and 4a (moist to dry open forest to woodland containing a mix of species including *Corymbia citriodora, E. carnea, E. propinqua, E. siderophloia, E. pilularis, E. acmenoides, E. major,* and *E. microcorys*). Dry forests were defined as broad vegetation groups 6, 7 (dry woodlands to open woodlands mostly dominated by *C. citriodora*) 8 and 8a (dry to moist woodlands and open woodlands dominated by *E. crebra, E. cullenii, and E. melanophloia*), 9a (open forest and woodlands on drainage lines and alluvial plains dominated by *E. tereticornis* or *E. camaldulensis*), and 11b.

Table 3 Estimates of MAI adopted and model parameters

Forest type	Silviculture	MAI of stands (m^3/ha/yr)			Weibull distribution parameter	
		Mean	Low	High	α	β
Moist tall	Untreated	1.7 [a]	0.50	3.0	n.a	n.a
Moist tall	Treated	3.50	2.00	7.0	2.0	1.80
Mixed hardwood	Untreated	0.30	0.10	1.0	1.6	0.25
Mixed hardwood	Treated	1.30	0.50	4.0	1.9	0.60
Spotted gum	Untreated	0.30	0.05	2.0	1.7	0.30
Spotted gum	Treated	1.30	0.50	2.0	1.3	1.03
Blue gum	Untreated	0.30	0.20	1.0	1.0	0.14
Blue gum	Treated	1.00	0.50	2.0	1.9	0.60
Gum-topped box	Untreated	0.15	0.05	0.4	1.9	0.12
Gum-topped box	Treated	0.80	0.40	1.5	2.5	0.46
Ironbark	Untreated	0.15	0.05	0.4	1.9	0.12
Ironbark	Treated	0.60	0.30	1.2	1.8	0.37

[a]The moist tall untreated forest is the only forest type where a normal probability density function provided the best fit. The standard deviation was 0.42. The MAIs for all other forest types were simulated using the Weibull distribution

Uncertainty about what fraction of the private native forest estate is managed for timber production, as well as the high proportion of hardwood log volume coming from private native forest and the low growth rates of untreated forests, means that standing timber volumes that are potentially available to industry at the time of writing are highly uncertain. Consequently, this assessment of potential long-term sawlog and pole yield has focussed on projected annual growth and has not considered the potential for (unsustainably) running-down current standing volumes.

Table 3 presents the consensus of experts regarding MAI of sawlog and pole volume in the six commercial forest types with and without silvicultural treatment. Average growth rates in well-managed private native forests range from 0.6 m^3/ha/y in ironbark forests to 3.5 m^3/ha/y in moist tall forests. The available literature and expert opinion have provided a range which reflects variation in site quality, historic management and species composition. A stochastic approach to project future log yields was necessary to capture this variability and provide decision-makers with the capacity to generate confidence intervals. However, there are no Queensland native forest merchantable growth datasets for different forest types and management regimes to which MAI probability distributions can be fitted. The use of probability distributions for uncertain model coefficients is preferable to deterministic approaches, even when data are scarce (Birge and Louveaux 1997; King and Wallace 2012). In the absence of data, probability density functions have been fitted to the minimum, mean and maximum MAI estimates for each forest type with and without silvicultural treatment. A normal probability density function provided the best fit for moist tall untreated forest, while the Weibull probability density function provided the best fit for silviculturally treated moist tall forests and all other forest types. The standard deviation (SD) for the normal distribution, and the scale parameter (α) and shape parameter (β) for the Weibull distribution were determined for each forest type such that the cumulative probability under the probability density function between the minimum and mean MAI was equal to 0.5, and the cumulative probability under the probability density function between the minimum and maximum MAI was equal to 1. The probability density function parameter levels are reported in Table 3.

Potential annual log yields (*Y*) for sawlogs and poles from private native forests in the study area have been estimated as follows:

$$Y = PNFMT * \left[\sum_{i=1}^{6} \left(\left((1 - ST) * FA_i * MAINT_i \right) + \left(ST * FA_i * MAIST_i \right) \right) \right] \tag{1}$$

where: *Y* is potential annual log yield (m^3/yr);

PNFMT is the proportion of private native forest managed for timber production (%);

ST is the proportion of private native forest managed for timber production that is also silviculturally treated (%);

FA_i is the area of forest type *i* (ha);

$MAINT_i$ is the MAI of forest type *i* when the forest is not silviculturally treated (m^3/ha/yr); and

$MAIST_i$ is the MAI of forest type *i* when the forest is silviculturally treated (m^3/ha/yr).

PNFMT was examined at the levels of 30, 40 and 50%, and *ST* was examined at the levels of 0–50% in 5 percentage point increments. The same levels of *PNFMT* and *ST* were adopted for all forest types in this assessment despite differences in productivity. Monte Carlo simulation was performed to produce 1000 estimates of *Y* for each combination of *PNFMT* and *ST*. This was achieved by generating 1000 random numbers between 0 and 1 for each forest type, in both their silviculturally treated and untreated conditions, for all combinations of *PNFMT* and *ST*. Each random number was then compared against the cumulative probability density function fitted for the relevant forest type, and the MAI associated with that cumulative probability was drawn for application in Eq. (1). The median and interquartile ranges were then determined for each combination of *PNFMT* and *ST*.

Results

Forest Types and Their Distribution

The area of private native suitable for timber harvesting depends on the presence of commercial tree species and legal restrictions under the Code. In accordance with the Code, the study area had a total harvestable private native forest area of 2,091,000 ha, with 1,886,400 ha considered commercially important (total harvestable private native forest area minus other harvestable forests). In the same study area, state owned forests cover around 2,424,600 ha. Spotted gum and iron-bark forests dominate private native forests in southern Queensland (Fig. 1), with harvestable areas of 693,000 ha and 641,500 ha, respectively (Table 4). The moist tall forest is the most productive forest type (Table 3), but has the lowest harvestable area (Table 4).

Figure 2 illustrates the distribution of harvestable and commercial private native forest among LotPlans in the study area. There were 17,665 LotPlans with greater than 20 ha of harvestable forest, accounting for the 1,886,400 ha of commercial and harvestable private forest. Twelve percent (2113) of these LotPlans had at least 20 ha of harvestable forest, but less than 20 ha commercial forest. There were 2950 LotPlans (17% of total) with at least 150 ha of commercial and harvestable forest, accounting for 66% of the commercial forest in the study area. There were 653 Lot-Plans (4% of total) with at least 500 ha of harvestable and commercial forest in the study area, accounting for 36% (680,000 ha) of the total, including 283,000 ha of spotted gum forest.

Forest Growth Rates and Potential Annual Log Yield With and Without Silvicultural Treatment

Figure 3 presents the medians and interquartile ranges derived from the Monte Carlo simulation with Eq. (1). The projected range of potential log yields at no silvicultural treatment is based on merchantable growth only and does not account for the potential to run-down existing standing volume. This log volume range (129,200 and 299,900 m^3/yr) is indicative of long-term log yields available under existing management, given the low rates of silvicultural treatment in private native forests, the prevalence of high-grading, and the uncertainty about area of harvestable private native forests managed for timber. The level of private sawlog and pole supply in 2017 was 195,800 m^3 (Francis et al. 2020a), which is the mid-range of these estimates.

These results indicate that silvicultural treatment can substantially increase log yields from commercial and harvestable private native forests (Fig. 3). For example, if 40% of harvestable private native forests are managed for timber production and 30% of these could be silviculturally treated, private native forests could potentially supply between 341,700 and 441,600 m^3/yr. This is substantially higher than current supplies from state and private land combined. Given differences in treatment responses between forest types, if treatments were concentrated in forest types with higher MAIs, potential log yields would be higher than those reported in Fig. 3. However, the projected increase in log yields for alternative levels of silvicultural treatment above the zero silvicultural treatment levels in Fig. 3 will not be achieved until about 20-years after commencement of a silvicultural treatment program. Log yields could be maintained within the zero silvicultural treatment range during the years before silviculturally treated forests are available for harvest.

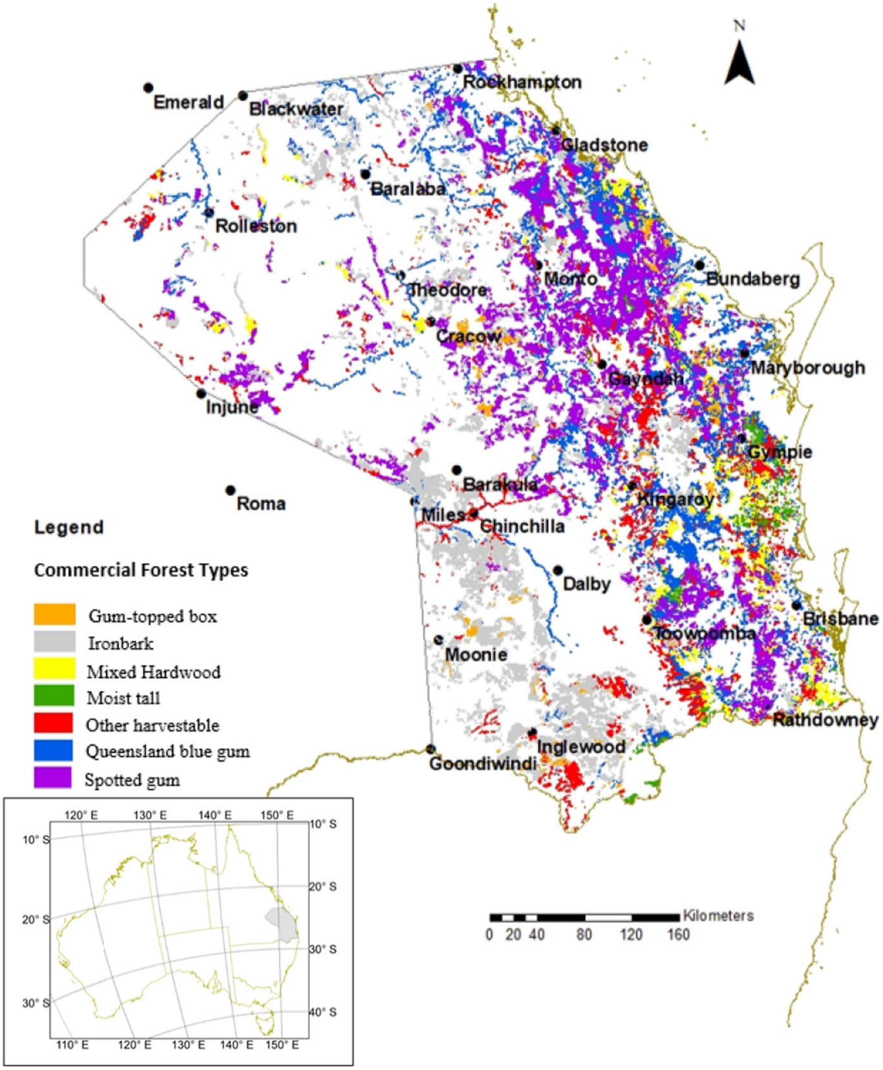

Fig. 1 The spatial distribution of harvestable private native forest in the study area

Discussion and Policy Implications

Findings of this paper suggest that southern Queensland private native forests can supply current hardwood log demand, and more than compensate for the transfer of state-owned production forests to the conservation estate, provided government policy is supportive of forestry and landholders are willing to perform silviculture and harvest timber. The potential has been estimated as a function of the proportion of the total harvestable private native forest estate managed for timber, the proportion of this area that is silviculturally treated, and the forest type.

Table 4 Harvestable area of private native forest in the study area by forest type

Forest type	Harvestable area[a] (ha)	Fraction of total (%)
Moist tall	33,400	1.6
Mixed hardwood	159,600	7.6
Spotted gum	693,000	33.1
Blue gum	253,300	12.1
Gum-topped box	105,600	5.1
Ironbark	641,500	30.7
Other harvestable forests	204,700	9.8
Total	2,091,000	100.0

[a]The harvestable area is the area of potentially harvestable private native forest in accordance with the Code, and not the actual area managed for timber production (which is unknown). Forests with slope exceeding 25 degrees have been excluded from these area estimates, and forest area (net of slope exclusions) for each forest type has been reduced by an additional 5% to account for stream buffer requirements of the Code

It is challenging to estimate actual log volumes that will be supplied to market in the future, because this will depend on the policy environment, timber markets and the forest management decisions of thousands of individual landholders who each have heterogeneous forest management objectives. This assessment has been based on Queensland forest policy and timber markets at the time of writing. A range of private native forest management and silvicultural treatment scenarios were considered in this assessment because there is a dearth of information about historic and future landholder management and harvest intentions. Previous research has suggested about 50% of the total harvestable area of private native forests may be being managed for timber production in southern Queensland (Bureau of Rural Sciences 2004; Queensland CRA/RFA Steering Committee 1998). Actual future log volumes will also depend on the availability of labour to perform the necessary silvicultural treatments. For example, if 40% of private native forests are managed for timber production, and 10% of these are silviculturally treated, then about 3770 ha must be treated annually.[2]. There are no publically available records of the area of private native forest that has been silviculturally treated, although anecdotal evidence suggests only a small area has been treated to date. Therefore, log volumes available to industry from private native forest cannot be predicted with the same level of precision as may be expected in the case of a large plantation estate managed by a single public or private owner.

Previously published estimates of potential annual log yield from private native forests in southern Queensland vary depending on study area and commercial forest definitions. For example, both Queensland CRA/RFA Steering Committee (1998) and Bureau of Rural Sciences (2004) examined yields within the SEQ Forest

[2] This annual rate of treatment is equal to one-twentieth of 10% of 754,600 ha.

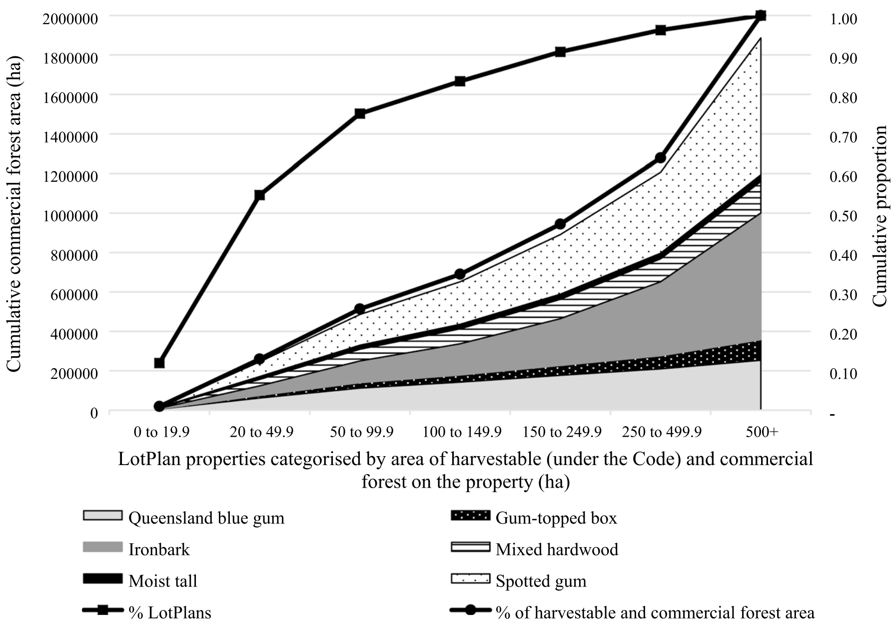

Fig. 2 Cumulative area of harvestable and commercial forest by LotPlans categorised by area of commercial forest on individual LotPlans

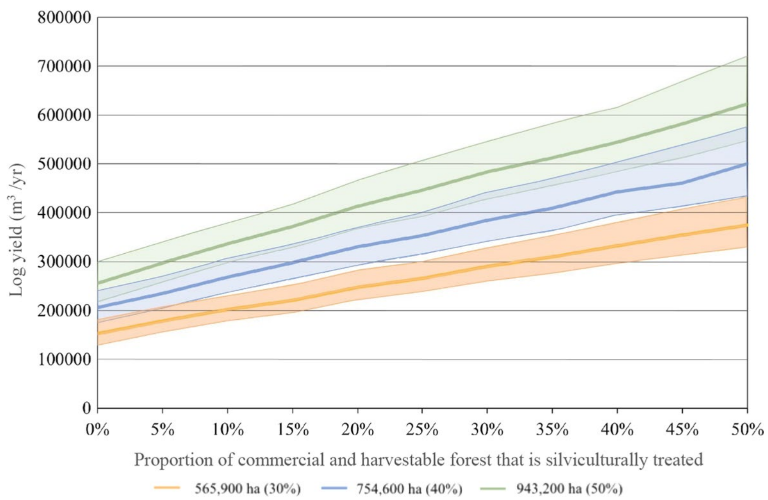

Fig. 3 Potential annual log yield given 30, 40 or 50% of commercial and harvestable private native forests are managed for timber production, at alternative proportions of silvicultural treatment. Note: The bold lines represent the median and the shaded areas represent the corresponding interquartile range. Overlapping colours represents overlap in the interquartile range between forest area managed for timber production scenarios

Agreement region (which is fully within the study area adopted in this paper), reporting the area of commercially important private native forest at 1.25 and 0.75 M ha, respectively. Assuming 50% of these forests were managed for timber and no silvicultural treatments were performed, Queensland CRA/RFA Steering Committee (1998) estimated the potential annual yield at 108,000 m^3, and Bureau of Rural Sciences (2004) at 50,000 m^3, representing MAIs of 0.17 and 0.13 m^3/ha/yr, respectively. These studies only considered compulsory sawlogs in their estimations of annual yield. For the larger study area adopted in this paper, and also assuming 50% of private native forests are managed for timber and that no silvicultural treatments are performed, the median potential annual log yield has been estimated at 256,000 m^3 (Fig. 3), representing a weighted average MAI of 0.26 m^3/ha/yr for all commercial log products (i.e. compulsory and optional sawlogs, poles, salvage and fencing materials) across the six commercial forest types. This estimate is consistent with Lewis et al. (2010), who reported growth rates of untreated spotted gum forest in southern Queensland at 0.35 m^3/ha/yr.

Empirical data, literature review and expert opinion revealed the potential for silvicultural treatments to increase MAI by a factor of between two and four. For example, this study revealed that if 50% of commercial and harvestable private native forests were managed for timber production, and half of that area was silviculturally treated, the median annual log yield starting about 20 years after commencement of a silvicultural treatment program could be about 623,000 m^3/yr. That represents a weighted average MAI of 0.66 m^3/ha/yr across the six commercial forest types, and a doubling of the current combined state and private log harvest. This weighted MAI estimate is consistent with the Bureau of Rural Sciences (2004) assertion that, with good management, rates of 'average [compulsory] sawlog growth of 0.5 to 1 m^3/ha/yr are not inconceivable over a large proportion of forests in SEQ' (p. vii).

Silvicultural treatments in private native forests in southern Queensland are financially viable (Francis et al. 2020b, 2022; Venn 2020), and potential new markets in southern Queensland for small logs for biomass energy (Ngugi et al. 2018) and the manufacture of laminated veneer lumber (LVL) (Venn et al. 2021) may facilitate increased levels of silvicultural treatment. The majority of private native forests in the study area are on properties where the main economic activity is beef cattle grazing (Lewis et al. 2020a, b, c). These landholders are more likely to consider managing their forests for timber if it could be shown that combined grazing and timber production resulted in a net increase in income Cockfield (2008b). Francis et al. (2022) found that the financial performance of southern Queensland farms managed as silvopastoral systems (by integrating cattle grazing with active native forest management for timber production) was greater than the financial performance of either grazing or timber alone.

Sound financial performance of native forestry with silvicultural treatments has not translated into landholder practices for three main reasons: (a) sovereign risk (uncertain future harvest rights); (b) long payback periods; and (c) limited forestry knowledge among landholders (Queensland CRA/RFA Steering Committee 1998; Bureau of Rural Sciences 2004; Thompson et al. 2006; Venn 2020). Changes in vegetation management regulations in Queensland since the 1990s have led to landholder uncertainty regarding future property rights and has been empirically linked to increased rates of land clearing (Productivity Commission 2004; Simmons et al. 2018). Future changes in Queensland forest policy could positively or negatively affect timber markets, the area of harvestable forest, the harvestable volume per hectare, required stem retention levels (affecting forest productivity and regeneration), and landholder decisions about how much forest to manage for timber and levels of silvicultural treatment to perform. For example, in 2021, a Native Timber Advisory Panel was established to advise the Queensland government on policy options for the native forest hardwood timber industry (Queensland Department of Agriculture and Fisheries 2021), and this may affect forestry opportunities in private native forests. The timber industry and landholders have long argued that encouragement of sustainable forest management practices requires certainty of harvest rights (Dare et al. 2017; Downham et al. 2019; Francis et al. 2020a). Without this certainty, landholders are less likely to invest in sustainable forest management, more likely to 'high-grade' their forest, and more likely to clear their forest where they have the right (e.g. category X vegetation in Queensland), so as to generate less risky income streams from cattle or cropping. In addition, the Queensland government commitment to transfer state-owned production forests to the conservation estate by 2024 (Queensland Department of Agriculture and Fisheries 2020) will directly impact log supply to industry and perhaps indirectly impact log demand by reducing the financial viability of some wood processors. These timber market impacts will affect forestry opportunities for landholders, as well as the regional forest industry.

Long payback periods are a disincentive for private native forest management. Venn (2020) proposed an annuity payment system for landholders to facilitate silvicultural treatments, similar to one proposed by Vanclay (2007) to stimulate conservation management in private native forests. A private or public investor with a long-term investment horizon would be required initially to fund the annuity payments and silvicultural treatments over the first 20 years. If industry (e.g. sawmills) were to contribute to these annuity payments, they could also become more active participants in the value chain by building relationships with private forest owners. Harvest revenues from treated forests would be sufficient to continue funding the program and provide a return to the investor after 20 years. The landholder would surrender their rights to manage timber to a professional forestry management organisation in return for the annuity payment. However, the landholder would maintain their right to access their forest for timber for domestic purposes and for non-timber uses, such as grazing and recreation. The contract would need to be for at least 20 years to ensure an adequate return on silvicultural investment. Modelling by Venn (2020) using the growth rates reported here, as well as industry-reported silvicultural treatment costs and stumpage prices, revealed the investor could earn a 5% per annum return on invested funds while paying landholders a $40/ha annuity. Transaction costs associated with such an investment scheme need to be investigated. Presumably a minimum forest area per landholder would be necessary for commercial viability. Landholders may also need to be aggregated spatially to facilitate economies of scale, both for transacting with the investor and for forest management.

In the absence of detailed information about heterogenous private native forest landholder attitudes, it is challenging to comment about the likely uptake of an annuity program by landholders that would require engagement with professional forest managers. Nevertheless, in Australia and internationally, managers of larger landholdings have been found more likely to engage in forest management for timber production (Cockfield 2008b; Dare et al 2017; Saulnier et al. 2017). In southern Queensland, smaller landholders closer to the coast do not rely solely on their properties for income, while larger landholders, who are generally located further from the coast, do predominantly rely on farm income (S. Ryan, Consultant, PFSQ, personal communication, 19 November 2021). Given 66% of commercial and harvestable private native forests in the study area are located on the 17% of LotPlans with at least 150 ha of commercial and harvestable forest, there is an opportunity to secure future hardwood log supplies for industry by targeting extension services and financial incentives at larger landholders. For example, only about 250,000 ha of silviculturally treated private native spotted gum forests (13.3%) of the commercial and harvestable private native forest estate in southern Queensland) would be required to perpetually supply the total public and private hardwood log volume that was supplied to industry in 2017.

In recent decades, state government-based private native forest extension programs have decreased. PFSQ (2000 to present) and Agforests (2005–2012) have stepped into this void and performed extension work and research trials with landholders. Nevertheless, most private native forest landowners still have poor knowledge about the potential financial benefits of a well-managed forest (Dare et al. 2017; Francis et al. 2022), including opportunities for joint production of cattle and timber in silvopastoral systems (Cockfield 2008a, b; Francis et al. 2022). Extension services that increase awareness of the potential financial returns and improve the capacity of landholders to manage their forests could encourage greater interest in forestry and silvopastoral systems. Cameron et al. (2019) reported that 100% of surveyed southern Queensland landholders were interested in learning forest management skills by attending field days, and 81% of respondents agreed that a training and extension program would improve their forest management practices.

Around the world, the management of forests for wood products temporarily affects forest composition and structure, and therefore ecosystem services relevant to biodiversity conservation, ecosystem functioning and carbon sequestration (Martinez Pastur et al. 2020). A biodiversity concern in Australia and elsewhere is loss of habitat trees (Neumann et al. 2021). However, forest management has been found to not impact the minimum recommended threshold for habitat trees in southern Queensland (Neumann et al. 2021). Venn (2023) asserted that a mix of selectively harvested, and conservation native forest areas would maximise Queensland's contribution to global efforts to protect biodiversity and mitigate climate risk. To encourage greater community trust in forest management practices and mitigate environmental concerns, landholders managing their forests could be encouraged to participate in forest certification through schemes, such as the Australian Forestry Standard or Forest Stewardship Council. However, individual landholders have typically been deterred from participating in such schemes due to high access costs and administrative loads (Dare et al. 2017). To overcome this barrier, landholders could work with groups, such as PFSQ, who are already certified. Industry could also contribute to the costs of forest certification to assist in developing relationships with landholders and demonstrate a long-term commitment to environmental, social and economic sustainability. Additionally, regional landholder associations could manage their forests together under one certification and share the associated costs. This approach has been adopted internationally, such as in the United States and Sweden, where small forest owners are group certified through umbrella organisations such as Forest Owner Associations (Lidestav and Berg Lejon 2011; Overdevest and Rickenbach 2006). Larger landholders are more likely to engage in forest certification in Australia and internationally (Lidestav and Berg Lejon 2011; Ma et al. 2012; Dare et al 2017).

The majority of privately-owned native forests are presently in poor productive condition, being overstocked and dominated by non-commercial stems (Jay 2017; Lewis et al. 2020b). Nevertheless, this study has demonstrated the potential for private native forests to supply relatively large volumes of hardwood logs to the Queensland timber industry. Estimation of actual log volumes harvested in the future would require thorough examination of the impacts of many social and economic factors that were beyond the scope of this study, including government policy regarding forest management and decarbonising industry, landholder management objectives and timber markets. An accommodating policy environment that overcomes perceived sovereign risk and facilitates silvicultural treatment is necessary to maintain and potentially increase private log supply. Fulton and Race (2000) and Emtage et al. (2006) have suggested that regional landholder typology studies would be useful to better understand landholder perspectives on forestry opportunities, constraints and necessary conditions to overcome those constraints. Informed by a typology study, targeted funding for native forest extension and silvicultural treatment programs for private landholders may be worthy of further evaluation.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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