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# Estimating potential harvestable biomass for bioenergy from sustainably managed private native forests in Southeast Queensland, Australia

Michael R. Ngugi[1*], Victor J. Neldner[1], Sean Ryan[2], Tom Lewis[3], Jiaorong Li[1], Phillip Norman[4] and Michelle Mogilski[5]

## Abstract

**Background:** Australia's energy future is at the crossroads and the role of renewable sources is in focus. Biomass from sustainably managed forests provide a significant opportunity for electricity and heat generation and production of liquid fuels. Australia has extensive native forests of which a significant proportion are on private land. However, there is limited knowledge on the potential capacity of this resource to contribute to the expansion of a biomass for bioenergy industry. In addition, there are concerns on how to reconcile biomass harvesting with environmental protection.

**Methods:** We used regional ecosystem vegetation mapping for Queensland to stratify harvestable forests within the 1.8 m hectares of private native forests present in the Southeast Queensland bioregion in 2014. We used a dataset of 52,620 individual tree measurements from 541 forest inventory plots collected over the last 10 years. Tree biomass was estimated using current biomass allometric equations for Australia. Biomass potentially available from selective sawlog harvesting and silvicultural treatment across the bioregion was calculated and mapped.

**Results:** Current sawlog harvesting extracts 41.4% of the standing tree biomass and a biomass for bioenergy harvest would retain on average 36% of felled tree biomass on site for the protection of environmental and fauna habitat values. The estimated area extent of harvestable private native forests in the bioregion in 2013 was 888,000 ha and estimated available biomass for bioenergy in living trees was 13.6 million tonnes (t). The spotted gum (*Corymbia citriodora* subsp. *variegata*) forests were the most extensive, covering an area of 379,823 ha and with a biomass for bioenergy yield of 14.2 t·ha$^{-1}$ (with approximately 11.2 t·ha$^{-1}$ of the biomass harvested from silvicultural thinning and 3 t·ha$^{-1}$ recovered from sawlog harvest residual).

**Conclusions:** Silvicultural treatment of private native forests in the Southeast Queensland bioregion, has the capacity to supply a large quantity of biomass for bioenergy. The availability of a biomass for bioenergy market, and integration of sawlog harvesting and silvicultural treatment operations, could provide land owners with additional commercial incentive to improve the management of private native forests. This could potentially promote restoration of degraded forests, ecological sustainability and continued provision of wood products.

**Keywords:** Renewable energy, Forest biomass, Woody biomass, Native forests, Silvicultural management, Biomass retention, Biobased

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* Correspondence: michael.ngugi@dsiti.qld.gov.au
[1] Department of Environment and Science, Queensland Herbarium, Mt Coot-tha Road, Toowong, Qld 4066, Australia
Full list of author information is available at the end of the article

## Background

Increasing dependency on fossil fuels (coal, natural gas, and oil), high costs, security of energy supply and the need to cut carbon dioxide emissions have driven a global quest for the substitution of fossil fuels with renewable energy alternatives. The use of renewable biomass for bioenergy production for heating, electricity production and liquid fuels is now subject to considerable interest and activity world-wide (Raison 2006; Janowiak and Webster 2010; Farine et al. 2012; Booth et al. 2014; Rothe et al. 2015; Murphy et al. 2015; Hayward et al. 2015; Crawford et al. 2016).

Currently, bioenergy only provides 0.9% of Australia's electricity generation. However, projections suggest it has the potential to provide between 19.8% and 30.7% of Australia's electricity requirement by 2050 (RIRDC 2010). National assessments of potential bioenergy resources in Australia including agricultural crops and residues, native grasses, forestry (plantations, short-rotation tree crops and native forests) and organic municipal solid wastes based on statistics published by Australian Bureau of Agricultural and Resource Economics (ABARE) (Farine et al. 2012; Crawford et al. 2016; AREMI 2017). Among these bioenergy resources, the specific role of forests as a renewable energy source has received widespread global attention (Fung et al. 2002; Janowiak and Webster 2010; Davis et al. 2012; Klockow et al. 2013; Meadows et al. 2014; Rothe et al. 2015). However there has been less attention in Australia where energy needs have largely been met by cheap coal and gas fossil fuels (Raison 2006). Action against climate change, rising energy costs and job creation are key driving forces towards the transition of the Australia economy from dependence on fossil fuels to renewable energy future. Consequently, the need for reliable localised information on the potential role of the Australia's expansive native forest resource in energy generation is overdue (Raison 2006; Rothe et al. 2015).

Australia is the seventh most forested country in the world with 125 million hectares of forest, equivalent to 16% of Australia's land area (National Forest Inventory 2013). The total area of Australia's native forest suitable and available for commercial wood production in 2010–2011 was 36.6 million hectares (DAWR 2015). This includes 29.1 million hectares of native forests under leasehold and private ownership (DAWR 2015), a resource that is often minimally managed (Clinnick et al. 2008). Improved silviculture involving thinning from below to release suppressed growth has been mooted to rejuvenate the growth of these forests and to restore their productivity and ecological values (Ryan and Taylor 2006).

Silvicultural management of private native forests in Queensland is crucial for ecological sustainability and provision of wood products in perpetuity (DNRM 2014). The commercial value of forest products currently harvested using selective method from native forests, namely sawlog, poles, girders, fencing material and piles, does not provide sufficient economic incentive for land owners to undertake non-commercial silvicultural improvement treatments. It is anticipated, that the emerging renewable energy market will provide an opportunity to utilize biomass from silvicultural thinning of forests, for bioenergy production. However little is known about the currently available stock of biomass in private native forests that can support the bioenergy industry in addition to their crucial role of environmental protection and the traditional role of timber production.

The proposition of biomass harvesting for bioenergy is often met with the apprehension that increasing demand for bioenergy would lead to over-utilisation of the relatively slow growing native forests (Hall 2002; Davis et al. 2012). In particular, there is concern that biomass harvesting has the potential to extract a greater proportion of a tree, and thereby jeopardise long-term soil productivity, water quality, and site-level biodiversity values (Benjamin 2010; Briedis et al. 2011; Klockow et al. 2013), including coarse wood materials crucial for fauna habitat (West et al. 2008; Briedis et al. 2011). On the contrary, current native hardwood forest harvest in Australia usually removes only a portion of the live tree from the site. Based on forest harvesting studies in the adjacent state of New South Wales (NSW) in Australia, it is estimated that a commercial timber harvest in native hardwood forests, extracts between 44% to 70% of whole tree biomass mainly for sawlog, veneer and pulp, and retains the remaining 30% to 55% of the tree on the forest floor in the form of bark, stump and crown (Ximenes et al. 2005; Ximenes et al. 2006; Ximenes et al. 2008). In Queensland, timber harvest of private native forests (excluding poles, girders, fencing material and piles) is mainly done for sawlog (does not include pulp and veneer) and only extracts high quality logs while retaining low-quality-log sections on the forest floor. This harvesting is regulated through a self-assessable vegetation clearing code of forest practice (DNRM 2014), to ensure the protection and maintenance of biodiversity values such as old-growth habitat trees, and soil and water resources. Hence, it is anticipated that biomass for bioenergy harvesting would be subject to this government regulation.

The main aim of this study was to provide an estimate of current harvestable biomass for bioenergy in living trees from private native forests within the Southeast Queensland bioregion. This is in recognition that in addition to biomass residual from wood processing (ABBA Qld 2016), residual biomass from sawlog harvesting and silvicultural thinning of poorly formed trees and those suppressing growth of timber trees (i.e., normal silvicultural treatment) has potential bioenergy value. Specific objectives were to: (1) map the extent and location of harvestable forest types within private native forests in the Southeast Queensland bioregion; (2) determine surplus recoverable biomass for bioenergy following conventional sawlog harvest; (3) determine and provide baseline biomass for bioenergy yield estimates from integrated sawlog and non-merchantable silvicultural treatment harvest; and (4) estimate the proportion of biomass retained on-site following a biomass for bioenergy harvest to address protection of soil productivity, water quality, and site-level biodiversity values.

## Methods

### Study area

The Southeast Queensland bioregion stretches from the town of Gladstone in the north (23°51'S, 151°13′E) to Springbrook National Park in the south (28°21'S, 153°6′ E) bordering New South Wales (Fig. 1). The total area of the bioregion is 6.7 million hectares. The climate is subtropical, characterised by hot humid summers (December to February) and cool, dry winters (June to August). The mean annual rainfall for the bioregion ranges from 1000 to 2400 mm and the monthly mean maximum temperature ranges from 22.9 °C – 31.3 °C at Gladstone and monthly mean minimum temperature ranges from 8.6 °C – 19.8 °C at Springbrook in the southern end of the bioregion (data obtained from Australian Bureau of Meteorology).

### Stratification of private native forests

This study only used forests that are in remnant condition (forests where dominant canopy has >70% of the height and >50% of the cover relative to the undisturbed state or reference condition (Eyre et al. 2015) of a native forest stand) or mapped as high value regrowth (the immediate lower category for a naturally regenerated site that is tracking towards the pre-clear vegetation structure and floristic composition and is approaching the remnant condition (Accad et al. 2017)). Remnant native forests in Queensland are consistently mapped at a scale of 1:100,000 using the regional ecosystem mapping framework (Neldner et al. 2017). Each regional ecosystem (RE) is a discrete vegetation community in a bioregion that is consistently associated with a particular combination of geology, landform and soil. This regional ecosystem mapping framework is the principal vegetation information resource used for planning, development and legislation in Queensland (QLD VM Act 1999). The mapping of each regional ecosystem is based on field survey, analysis of aerial photographs and satellite imagery, and assessment of other data such as geology and soil mapping and historical survey plans. Many regional ecosystems include one or more vegetation communities that are in association within a regional ecosystem that have similar structure and floristics and occur within the same land zone. Broad Vegetation Groups (BVG) are a higher-level grouping of regional ecosystems and vegetation communities (Neldner et al. 2017). The BVG with a nominal scale of 1:1 million were used to provide an overview of the extent of harvestable private native forests across the southeast Queensland bioregion (Fig. 1).

### Harvestable native forests in Southeast Queensland

The harvesting of timber on remnant private native forests in Queensland is regulated by the government under the Vegetation Management Act 1999 (QLD VM Act 1999) through “Managing a native forest practice: A self-assessable vegetation clearing code” effective from 8 August 2014 (DNRM 2014). The code provides mandatory practices necessary for continued timber production within conservation and sustainable development framework that ensures prevention of loss of biodiversity and ecological processes, maintenance of water quality, prevention of soil and land degradation, and maintenance of healthy forest structure and species composition. The code also provides a listing of the only regional ecosystems in hardwood forests in which selective timber harvesting and thinning is permitted. These are forests dominated by genus *Eucalyptus*, *Corymbia*, *Lophostemon*, *Syncarpia* and *Angophora*.

### Mapping the spatial extent of private native forests in Southeast Queensland (SEQ)

The extent of the private native forest resource in SEQ bioregion was mapped using ArcGIS Version 10.4.1. All the datasets were clipped to the SEQ bioregion boundary (Version 5.0). Woody vegetation cover was mapped using high value regrowth dataset (HVR, unpublished data of Queensland Herbarium, July 2016) and the 2014 foliage projective cover (FPC) dataset (FPC14, Statewide Landcover and Trees Study, SLATS). Values of FPC ≥30% were extracted from FPC14 to represent tree cover and polygons with areas <5 ha were excluded or merged to adjacent polygons. A native forests (NF) feature class was created by removing plantation areas from woody vegetation coverage. A private native forest feature class was created by selecting freehold land parcels (FH) from the digital cadastral database (DCDB, July 2016). All individual land parcels with a woody vegetation cover of <5 ha were excluded. This allowed a digital coverage of the private native forests present in 2014 to be produced.

To delineate harvestable areas with slope < 25° (this is the slope threshold set by the code of practice to reduce risk of soil erosion, (DNRM 2014)), a raster dataset for slope was generated from 1 s SRTM (Shuttle Radar Topography Mission, NASA) derived hydrological Digital

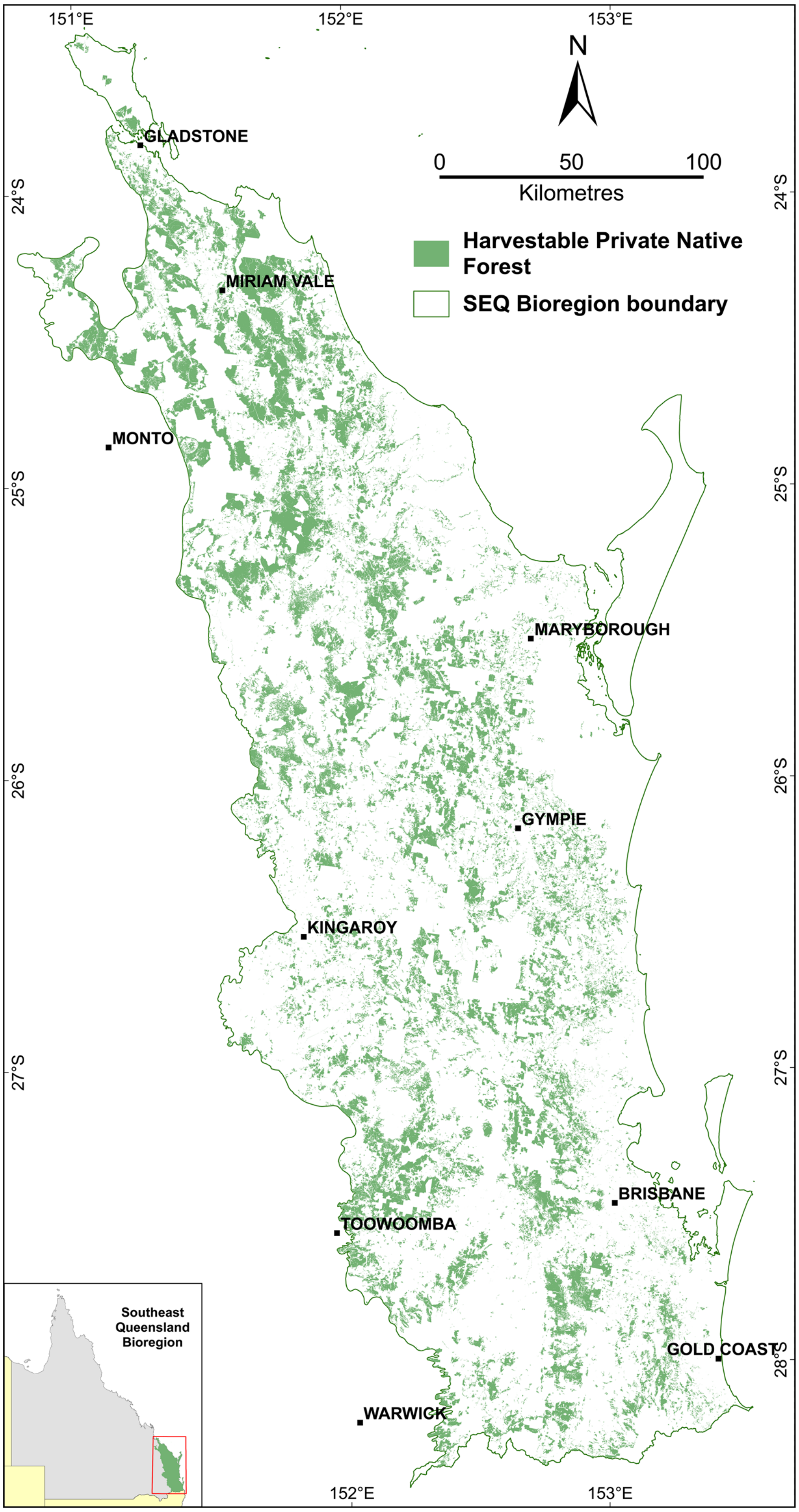

**Fig. 1** Location of harvestable private native forests in the Southeast Queensland bioregion mapped in 2014

Elevation Model (DEM-H, Version 1.0, 2011). Using remnant regional ecosystems vegetation mapping dataset (Remcov15, Accad et al. 2015), harvestable private native forests that are relatively intact and have been mapped as being in remnant condition were designated. All high value regrowth forests in non-remnant condition within the mapped harvestable private native forest area were assigned a regional ecosystem using Pre-clear Regional Ecosystem Mapping (Version 10.0) (Queensland Herbarium 2016). Finally, mapping out all regional ecosystems in which a native forest timber harvesting is permitted was based on the listing provided by the native forest code of practice (DNRM 2014). In order to aggregate regional ecosystems into broader vegetation types we used the broad vegetation group classification (Neldner et al. 2017).

### Native forest inventory datasets

A total of 541 native forest inventory plots of varying sizes, mainly located in mapped remnant forest (Accad et al. 2015), and a few in high value regrowth (a condition indicating that these forests close to attaining remnant state) forests were used. These data were collected in the last 10 years for informing private native forest management and contain 53,130 individually measured trees. Most of the measured forests were in remnant condition and may have a history of selective harvesting of conventional forest products, and few were high value regrowth forests. Private Forest Services Queensland (PFSQ), provided 456 inventory plots located at over 35 private properties of varying sizes. These plots sampled at least 43 regional ecosystems across the SEQ bioregion. The plots were 10 m wide and ranged in lengths from 37 m to 2596 m and in area from 0.037 to 2.6 ha, and were distributed in harvestable private native forests. A 100-m length measuring tape was laid out from the start point along a determined bearing and re-laid until the end of the plot. A width of 5 m on each side of the tape was marked using flagging tape. All individual trees with diameter at breast height (dbh, 1.3 m) >4 cm were measured and visually assessed for potential environmental or commercial use. Each tree was then assigned a product category and a recommendation to either harvest or retain for future use. The product categories recorded were: sawlog, salvage sawlog, pole, pile, fencing use, habitat tree, biodiversity retention (species composition) and silvicultural treatment. Merchantable log length was recorded for individual trees that could be harvested (at the time of assessment, or in the future).

The Department of Agriculture and Fisheries (DAF), provided 51 plots located at 13 properties, sampling 11 harvestable regional ecosystems in private native forests in SEQ. The plots ranged in area from 0.04 to 0.25 ha and included both rectangular and circular plots. The minimum dbh varied between sites, but was ≥10 cm at most sites, and as low as 2 cm at some sites. Each tree was assessed for commercial utilisation and only the individual trees marked for silvicultural treatment were used for the study. A third set of data used for the study included 34 plots measured in publically managed (Crown) native forests in Southeast Queensland. All the plots were rectangular and varied in size from 0.2 to 0.5 ha and collected in the last 50 years as a part of the long-term Native Forest Permanent sample Plots (NFPP) network (Ngugi et al. 2014; Ngugi et al. 2015). All measured individual trees had dbh >10 cm and only individual trees marked for thinning were used for this analysis. Since most data from these plots were collected prior to the establishment of the native forest practice Code (DNRM 2014), data for each plot were scrutinised to ensure retention of habitat tree stems as required by the native forest practice Code (DNRM 2014).

### Estimating aboveground tree biomass

Accurate ground-based estimates of biomass are important for management of forest biomass change and biomass products. Previous biomass estimations for native forests in state forests in Queensland (Ngugi et al. 2014) utilized 12 different allometric equations. Since then and in order to simplify biomass estimation, Paul et al. (2016) has developed generalised allometric equations for native forests in Australia. These generalised models were derived from destructive timber harvesting of 15,054 individual trees and shrub from managed and natural woody ecosystems across 826 sites in terrestrial ecoregions in Australia. Using five broad categories of plant functional types (trees of the genus *Eucalyptus* and closely related genera, shrubs, multi-stemmed trees, other trees with high wood density, and other trees with low wood density) the relationship between biomass and stem diameter was found to fit a simple power-law model that explained 84%–95% of biomass variation (Paul et al. 2016). Additionally, there was little improvement to this generic model when other plant variables such as height and bole wood density, or site characteristics were included. Consequently, the separate allometric equations belonging to various plant functional types based on Paul et al. (2016) are used in this analysis are presented below.

For single-stemmed hardwood individual trees from the genus: *Eucalyptus*, *Corymbia*, *Angophora* and *Lophostemon* (*N*: 6004 trees, $D_{1.3}$ range: 0.5–169 cm),

$$\mathrm{AGB_{indiv}}\,(\mathrm{kg})\ \text{of}\ F_{\mathrm{Euc}} = \exp\left[-2.016 + 2.375\ \ln\left(D_{1.3}\right)\right] \times 1.067 \tag{1}$$

For other generally single-stemmed individual tree species (including *Alphitonia*, *Acacia* and *Allocasuarina*, with relatively high wood density (mean 0.67 g·cm$^{-3}$) ($N$: 503, $D_{1.3}$ range: 1.6–123.4 cm),

$$\mathrm{AGB}_{\mathrm{indiv}}\ (\mathrm{kg})\ \text{of}\ F_{\text{other-H}} = \exp\left[-1.693 + 2.220\ \ln\left(D_{1.3}\right)\right] \times 1.044 \tag{2}$$

For other tree species from the genera of *Pinus* and *Araucaria* with relatively low stem wood density (mean 0.40 g·cm$^{-3}$) ($N$: 767, $D_{1.3}$ range: 2.3–60.4 cm),

$$\mathrm{AGB}_{\mathrm{indiv}}\ (\mathrm{kg})\ \text{of}\ F_{\text{other-L}} = \exp\left[-2.573 + 2.460\ \ln\left(D_{1.3}\right)\right] \times 1.018 \tag{3}$$

where, $\mathrm{AGB}_{\mathrm{indiv}}$ (kg) is total aboveground biomass (oven-dry weight of an individual plant) in kilograms; $F_{\mathrm{Euc}}$, $F_{\text{other-H}}$ and $F_{\text{other-L}}$ are plant functional types (Gitay and Noble 1997); $D_{1.3}$ is diameter at breast height (1.3 m) in centimetres. Wood density for all trees species listed in our combined dataset were obtained from Australia National Carbon Accounting System Technical Report on state of knowledge on wood density (Ilic et al. 2000).

### Estimating potential harvestable biomass within each regional ecosystem

Each inventory plot from the DAF and NFPP datasets was assigned a regional ecosystem (RE) and BVG information by intersecting plot location data with pre-clear RE mapping. Since the PFSQ dataset had coordinates for both the start and the finish points of each inventory strip, these two points were intercepted with the pre-clear RE mapping, providing RE information on both points. Additionally, the list of RE traversed by each strip were also recorded and associated with the strip.

For each inventory plot, the total biomass from all the individual trees that were marked for silvicultural treatment was determined using whole tree allometric equations and scaled to a hectare. The biomass value was then assigned to all REs intercepted or traversed by the inventory plot. For areas with two or more REs (heterogeneous polygons) (Neldner et al. 2017), the biomass value was also assigned to non-dominant REs that were represented in a polygon by a proportion > 40%. Using this method, 68 of the 78 harvestable REs were assigned a biomass value. The remaining REs without data (RE 12.3.1, 12.11.11, 12.11.12, 12.5.13, 12.8.13, 12.9–10.16, 12.11.8, 12.12.8, 12.9–10.11) represented 6.2% of the harvestable area.

### Estimating the proportion of tree biomass currently harvested in a sawlog only harvest in Queensland

A dataset from PFSQ containing 2418 individual trees with assigned product categories of quality sawlog was used. For each tree, the measured length of harvestable log was used for estimating the biomass harvested for sawlog. The remaining tree components were used for estimating biomass retained on-site following a sawlog harvest operation. The whole tree biomass for these trees was calculated using individual tree allometric equations (Eqs. 1, 2, and 3). The volume of the recoverable sawlog was calculated using Huber's formulae (Husch et al. 2002), and converted to dry weight by multiplying log volume by wood density for each species (Ilic et al. 2000). Biomass retained on-site as sawlog residual was the difference between whole tree biomass and the harvested biomass. The mean proportion of whole tree biomass that is harvested as a sawlog was derived from these estimates.

### Estimating potential proportion of individual tree biomass harvestable for bioenergy in Queensland

Current timber harvesting in private native hardwood forests in Queensland is mainly for sawlog. This harvest removes a high quality sawlog portion and retains a considerable portion of the felled tree on-site as non-merchantable. This is unlike in adjacent state of New South Wales (NSW) where native hardwood forest harvesting removal can include removal of high quality trees for veneer, and others for sawlog and a small fraction for pulp, and individual trees are harvested up to the non-merchantable upper diameter (Ximenes et al. 2008). Following a similar approach to NSW, a portion of the non-harvested tree biomass during sawlog harvesting in Queensland can potentially be harvested for biomass for bioenergy while still retaining the upper top portion of the tree for environmental purposes. The amount of tree biomass that can be recovered for commercial use and the portion retained for environmental purposes can be estimated by partitioning aboveground tree biomass into proportions: commercial stem log, stump, bark and crown. Since no comprehensive biomass harvest partitioning data were available for native hardwood forests in Queensland at the time of this study, generalised estimates from the NSW were used. These were based on detailed published data for two common commercial timber species (*Corymbia maculata* (spotted gum) and *Eucalyptus obliqua* (messmate)) in NSW (Ximenes et al. 2008).

## Results

### Area of harvestable private native forests

The estimated total area of private native forests in the SEQ bioregion based on 2014 mapping was 1,804,152 ha. Approximately 887,509 ha of this area is in regional ecosystems where timber harvesting is currently permitted by the code of practice (DNRM 2014). Using the described mapping methodology and a list of regional ecosystems in which timber harvesting is permitted, the extent of harvestable native forests on privately owned lands based on 2014 extent mapping was estimated at 844,732 ha. This includes forest patches >5 ha and on slopes <25 degrees (restricted threshold slope to reduce soil erosion risk). Moist open forests dominated by *Corymbia citriodora* (spotted gum) (10b) with a harvestable area of 378,823 ha had the highest area extent (43%, Table 1). The area extent of spotted gum forests was about four times that of moist eucalypt open forests dominated by *Eucalyptus siderophloia* (9a), which was the BVG with the second highest extent (Table 1).

### Estimated total aboveground biomass before and after forest harvest in private native forests in the Southeast Queensland bioregion

The estimated total aboveground biomass for the various broad vegetation groups based on available before and after a forest harvest practice data are presented in Table 2. Total aboveground stand biomass before the forest practice operations ranged from 14.1 t·ha$^{-1}$ in dry woodlands dominated by ironbark species (12a) to 123.1 t·ha$^{-1}$ in open forests on alluvial plains (22a), which have limited area extent (Tables 1 and 2). Most of these estimates were characterised by high variability between sites as shown by the standard error (Table 2) that ranged from 2% to 68% of the mean. The estimated mean biomass before harvest in the extensive moist open forests dominated by spotted gum species (10b) was 37.1 t·ha$^{-1}$. High biomass was also recorded on complex notophyll vine forest with *Araucaria* species (2a, 77.8 t·ha$^{-1}$) and on open forests dominated by stringybarks (9 g, 77.9 t·ha$^{-1}$) compared to other forest types (Table 2) but these forests are less extensive (Table 1). The estimated proportion of biomass retained during forest practice operations ranged from 37.2% ± 3.0% to 74.6% ± 6.1% of the biomass before harvest and that of spotted gum forest was 52.1% ± 2.5% (Table 2).

### Estimating individual tree biomass harvest partitions

The average proportion of whole tree aboveground biomass that can be harvested from hardwood forests for commercial use based on NSW's data shown in Table 3 was approximately 64.0%. Hence the average biomass proportion retained on-site as stump, bark and crown is 36%.

In Queensland, the proportion of individual tree biomass harvested as sawlog in private native forests using current practice was estimated from inventory data ($N = 2418$ trees) that recorded lengths of recoverable timber for each suitable tree in a plot. The mean proportion of aboveground biomass harvested for sawlog only was 41.4% of whole tree biomass. This amount is approximately 35% less the estimated harvestable commercial stem log amount from native hardwood forest trees in NSW (Table 3). Relative to the harvestable commercial biomass from NSW forests of 64% (Table 3), approximately 22.6% of potentially commercial biomass is currently not harvested in Queensland native forests. This portion can be used for other wood products such as small size veneer or for bioenergy and yet retain 36% of the whole tree biomass on-site for environmental values.

### Estimated biomass for bioenergy recovered from a sawlog harvest operation

The recoverable biomass for bioenergy from residual of trees harvested for sawlog only varied from 1.3 to

**Table 1** Estimated area of private native forest where timber harvesting is allowed and the harvestable area with slope < 25 degrees for corresponding broad vegetation groups (BVG) in Southeast Queensland in 2013

| BVG | Vegetation description and dominant species | Allowed area (ha) | Harvest area (ha) |
|---|---|---|---|
| 2a | Complex evergreen notophyll vine forest with *Araucaria cunninghamii* (hoop pine) | 26,203 | 22,253 |
| 8a | Wet tall open forest dominated by *Eucalyptus grandis* or *E. saligna* | 5990 | 5877 |
| 8b | Moist open forests to tall open forests dominated by *Eucalyptus pilularis* | 22,825 | 21,189 |
| 9a | Moist eucalypt open forests dominated by *Eucalyptus siderophloia* plus others | 92,437 | 83,859 |
| 9 g | Forests dominated by stringybarks or mahoganies | 58,367 | 56,383 |
| 9 h | Dry woodlands dominated by *Eucalyptus acmenoides* plus others | 85,458 | 82,754 |
| 10b | Moist open forests dominated by *Corymbia citriodora* (spotted gum) | 378,823 | 364,261 |
| 11a | Open forests dominated by *Eucalyptus orgadophila*, *E. tereticornis* and others, mainly on basalt | 17,555 | 13,921 |
| 12a | Dry woodlands dominated by ironbarks, mainly on sandstone and weathered rocks | 22,194 | 21,493 |
| 13c | Woodlands of *Eucalyptus crebra*, *E. drepanophylla*, mainly on metamorphic or acid igneous rocks | 77,953 | 73,670 |
| 13d | Woodlands dominated by *Eucalyptus moluccana* | 42,159 | 41,746 |
| 16c | Woodlands dominated by *Eucalyptus tereticornis* | 52,426 | 52,208 |
| 22a | Open forests and woodlands dominated by *Melaleuca quinquenervia* | 5120 | 5120 |
|  | Totals | 887,509 | 844,732 |

**Table 2** Summary of the estimated biomass (mean ± standard error) before and after a forest practice operation in private native forests in Southeast Queensland bioregion

| Broad Vegetation group (1: 1 M) | Sites ($n = 336$) | Biomass before harvest (t·ha$^{-1}$) | Biomass after harvest (t·ha$^{-1}$) | Biomass retained (%) |
|---|---|---|---|---|
| 2a Complex notophyll vine forests | 17 | 77.8 ± 19.5 | 31.5 ± 7.1 | 42.2 ± 3.4 |
| 8a Wet tall open eucalypt forests | 16 | 58.3 ± 11.5 | 22.5 ± 5.1 | 37.2 ± 3.0 |
| 8b Moist open forests *E. pilularis* | 47 | 36.5 ± 6.9 | 14.5 ± 3.0 | 40.0 ± 2.9 |
| 9a Moist open eucalypt forests | 37 | 68.7 ± 10.9 | 30.8 ± 4.2 | 48.0 ± 2.2 |
| 9 g Open forests - stringybarks | 10 | 77.9 ± 14.6 | 36.9 ± 6.8 | 49.7 ± 3.9 |
| 9 h Dry woodlands – eucalypts | 42 | 44.9 ± 7.3 | 20.6 ± 3.4 | 42.2 ± 2.9 |
| 10b Moist open forests *Corymbia* spp | 86 | 37.1 ± 3.6 | 14.9 ± 1.2 | 52.1 ± 2.5 |
| 12a Dry woodlands- ironbarks | 4 | 14.1 ± 2.7 | 10.0 ± 1.2 | 74.6 ± 6.1 |
| 13d Woodlands of *E. moluccana* | 53 | 48.2 ± 4.9 | 25.0 ± 2.5 | 54.5 ± 1.8 |
| 16c Open woodlands on floodplains | 17 | 71.6 ± 7.5 | 33.0 ± 4.1 | 45.3 ± 2.1 |
| 22a Open forests on alluvial plains | 2 | 123.1 ± 83.6 | 54.3 ± 36.6 | 44.4 ± 0.4 |
| Mean | | 54.9 ± 13.1 | 24.4 ± 6.1 | 48.3 ± 3.3 |

11.8 t·ha$^{-1}$ among the harvestable BVGs (Table 4). Although potentially available biomass for bioenergy was highest in forests dominated by *Eucalyptus grandis* or *E. saligna*, and *E. pilularis* which had a yield of 11.8 t·ha$^{-1}$ and 7.8 t·ha$^{-1}$, respectively, these forests only cover 5% of total harvestable forest area. In contrast, the estimated biomass for bioenergy harvested from spotted gum forests (10b) was 3.0 t·ha$^{-1}$, but these forest comprise 44% of harvestable private native forests in SEQ (Tables 1 and 4). The overall estimated average biomass for bioenergy that can be recovered following a sawlog harvest operation was 4.3 ± 1.0 t·ha$^{-1}$.

## Estimated stocking and total harvestable biomass for bioenergy for each broad vegetation group

The estimated stocking of harvestable private native forest stands before harvest ranged from 228 to 680 trees·ha$^{-1}$. Following proposed harvest and silvicultural treatment, the residual stocking ranged from 40 to 233 trees·ha$^{-1}$ (Table 5). The Code of practice for native forest harvesting (Table 2 of the Code of practice (DNRM 2014)) mandates a minimum retention average of 150 trees·ha$^{-1}$ and no less than 50 trees·ha$^{-1}$ should be left standing on a site. Hence the results presented in Table 5 indicate that stocking after harvest in most BVGs, fell below the minimum retention numbers required by the Code (150 trees·ha$^{-1}$) but it was in most cases above the minimum threshold of 50 trees·ha$^{-1}$. These findings suggest the need for careful consideration during pre-operation tree marking to ensure that the required minimum retention rate is adhered to.

The estimated average of harvestable biomass for bioenergy (sawlog operation + silvicultural treatment) that can be extracted from a broad vegetation group ranged from 11.0 t·ha$^{-1}$ in the dry woodlands dominated by ironbarks, mainly on sandstone and weathered rocks to as high as 43.2 t·ha$^{-1}$ in the wet tall open forest dominated by *Eucalyptus grandis* or *E. saligna* (Table 5). The estimated biomass yield from spotted gum forest (10b) was 14.2 ± 0.8 t·ha$^{-1}$. The overall average of harvestable biomass for bioenergy from the integration of silvicultural treatment with biomass residual from sawlog harvesting from all private native forest types was estimated at 20.3 ± 3.3 t·ha$^{-1}$.

## Distribution of biomass for bioenergy from private native forests among local government areas in SEQ

The total harvestable biomass for bioenergy estimated from the entire bioregion was 13,575,000 t. Distribution of harvestable biomass among local government areas in SEQ bioregion varied from 19,000 t in Western Downs Shire to 2,444,000 t in Gladstone Regional Council (Fig. 2). Five local governments with estimated biomass

**Table 3** Proportions of oven-dry biomass in the aboveground components of individual trees of *Corymbia maculata* (spotted gum) and *Eucalyptus obliqua* (messmate) in native forests in eastern New South Wales, Australia (Figure three of Ximenes et al., 2008)

| Species | Commercial stem log (%) | Stump (%) | Bark (%) | Crown (%) | Trees ($N = 160$) |
|---|---|---|---|---|---|
| Spotted gum | 58.2 | 4.6 | 7.2 | 30.1 | 125 |
| Messmate[a] | 70 | 2.4 | 7.3 | 20.3 | 35 |
| Averages | 51.9 | 3.5 | 7.3 | 25.2 | |

[a] commercial log include pulpwood

**Table 4** Estimated harvestable biomass (mean ± standard error) for bioenergy recovered following sawlog harvest within harvestable regional ecosystems grouped into broad vegetation groups (BVG) in Southeast Queensland bioregion

| BVG | Vegetation description and dominant species | Sites ($n = 285$) | Residual biomass ($t{\cdot}ha^{-1}$) |
|---|---|---|---|
| 2a | Complex evergreen notophyll vine forest with *Araucaria cunninghamii* (hoop pine) | 7 | 5.1 ± 0.7 |
| 8a | Wet tall open forest dominated by *Eucalyptus grandis* or *E. saligna* | 7 | 11.8 ± 3.9 |
| 8b | Moist open forests to tall open forests dominated by *Eucalyptus pilularis* | 7 | 7.8 ± 2.3 |
| 9a | Moist eucalypt open forests dominated by *Eucalyptus siderophloia* plus others | 38 | 4.6 ± 0.6 |
| 9 g | Forests dominated by stringybarks or mahoganies | 8 | 2.7 ± 0.3 |
| 9 h | Dry woodlands dominated by *Eucalyptus acmenoides* plus others | 65 | 3.0 ± 0.3 |
| 10b | Moist open forests dominated by *Corymbia citriodora* (spotted gum) | 69 | 3.0 ± 0.3 |
| 11a | Open forests dominated by *Eucalyptus orgadophila*, *E. tereticornis* and others, mainly on basalt | 1 | 1.3 |
| 12a | Dry woodlands dominated by ironbarks, mainly on sandstone and weathered rocks | 7 | 2.2 ± 0.2 |
| 13d | Woodlands dominated by *Eucalyptus moluccana* | 47 | 2.8 ± 0.3 |
| 16c | Woodlands dominated by *Eucalyptus tereticornis* | 26 | 3.1 ± 0.4 |
| 22a | Open forests and woodlands dominated by *Melaleuca quinquenervia* | 2 | 4.3 ± 1.2 |
|  | Mean |  | 4.3 ± 1.0 |

of greater than one million tonnes are presented in (Table 6).

## Discussion

Past attempts to estimate timber resources in private native forests have been limited by lack of inventory data and long-term monitoring programs in contrast to most state owned native forests in Australia (MbaC 2003; Raison 2006; Ngugi et al. 2015). The methodology used in this study to map the extent of privately owned native forests provides a consistent approach for mapping the harvestable forest resource that can be applied elsewhere in Queensland. This approach utilized the regional ecosystem spatial mapping dataset for Queensland to stratify the entire forest estate into broad vegetation groups (Table 1) and utilized inventory data collected from 541 plots on native forests. This study however did not exclude buffer zones along watercourses because of the prohibitive computing resources necessary to handle drainage dataset for the entire bioregion. However, while exclusion of buffer zones would result in some reduction of harvestable area, the majority of watercourses in these mainly dry sclerophyll forests are mapped as stream type of order 1 to 4, and have a buffer zone requirement of between 0 and 5 m stipulated by the Code of Practice (DNRM 2014). Future detailed resource maps targeting

**Table 5** Summary of forest statistics derived from inventory data showing number of stems per hectare (mean ± standard error) before and after harvest and the estimated potential harvestable biomass for bioenergy (total from silvicultural treatments and after sawlog harvest) for each broad vegetation group in Southeast Queensland bioregion

| Broad Vegetation group (1: 1 M) | Sites ($n = 450$) | Stocking before harvest ($stems{\cdot}ha^{-1}$) | Stocking after harvest ($stems{\cdot}ha^{-1}$) | Harvestable biomass for bioenergy ($t{\cdot}ha^{-1}$) |
|---|---|---|---|---|
| 2a Complex notophyll vine forests | 8 | 281 ± 47 | 64 ± 11 | 28.4 ± 4.3 |
| 8a Wet tall open eucalypt forests | 9 | 492 ± 127 | 168 ± 65 | 43.2 ± 5.8 |
| 8b Moist open forests *E. pilularis* | 14 | 336 ± 57 | 135 ± 38 | 29.1 ± 3.6 |
| 9a Moist open eucalypt forests | 69 | 297 ± 13 | 125 ± 9 | 20.8 ± 1.3 |
| 9 g Open forests - stringybarks | 8 | 264 ± 30 | 83 ± 7 | 18.7 ± 3.5 |
| 9 h Dry woodlands – eucalypts | 81 | 266 ± 10 | 96 ± 3 | 14.0 ± 0.8 |
| 10b Moist open forests *Corymbia* spp | 156 | 383 ± 35 | 109 ± 8 | 14.2 ± 0.7 |
| 11a Open forests mainly on basalt | 1 | 228 | 40 | 19.0 |
| 12a Dry woodlands- ironbarks | 8 | 230 ± 20 | 116 ± 25 | 11.0 ± 1.8 |
| 13c Woodlands of *E. crebra* | 2 | 481 ± 199 | 147 ± 65 | 13.4 ± 5.6 |
| 13d Woodlands of *E. moluccana* | 64 | 271 ± 12 | 94 ± 4 | 14.5 ± 0.8 |
| 16c Open woodlands on floodplains | 28 | 241 ± 39 | 61 ± 7 | 14.0 ± 1.3 |
| 22a Open forests on alluvial plains | 2 | 218 ± 49 | 61 ± 6 | 23.1 ± 10.1 |

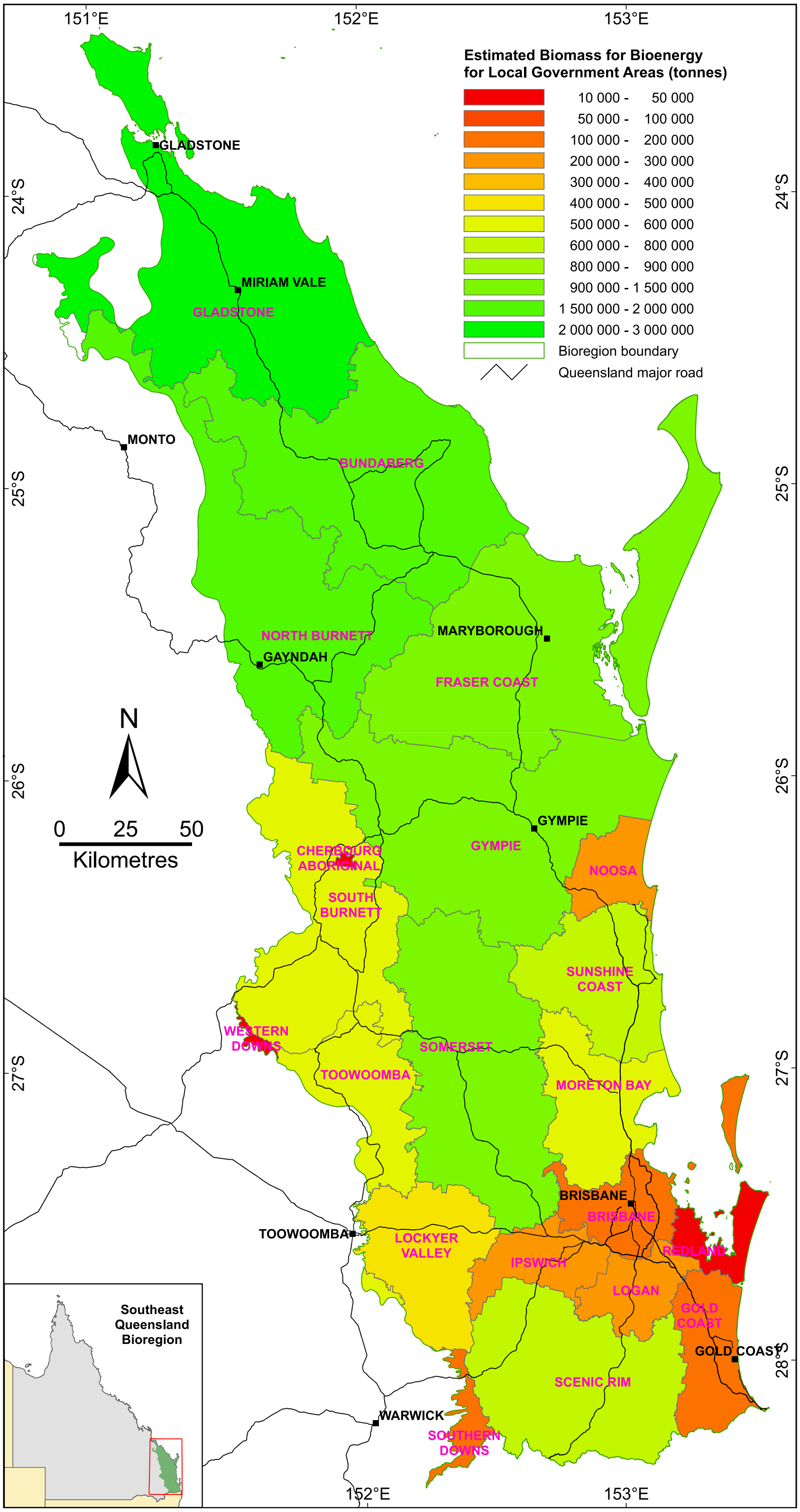

**Fig. 2** Estimated biomass for bioenergy from remnant and high value harvestable private native forests in local government areas within southeast Queensland

**Table 6** Summary of estimated total area of privately owned native forests where timber harvesting is allowed and for harvestable areas with slope < 25 degrees (based on 2013 vegetation cover) in local government area in Southeast Queensland with estimated biomass for bioenergy >1 million tonnes

| Local Government Area | Total forest area (ha) | Harvestable forest area (ha) | Biomass for bioenergy (t) |
|---|---|---|---|
| Gladstone Regional | 173,000 | 167,000 | 2,444,000 |
| North Burnett Regional | 112,000 | 108,000 | 1,562,000 |
| Bundaberg Regional | 109,000 | 107,000 | 1,558,000 |
| Gympie Regional | 82,000 | 77,000 | 1,326,000 |
| Somerset Regional | 68,000 | 64,000 | 1,085,000 |

local government areas of interest should exclude waterway buffer zone areas from maps of harvestable forest areas.

Sawlogs are the primary forest product harvested in Queensland's private native forests (Ryan and Taylor 2006). The standards for sawlog are high and not many individual trees meet them – they need to be straight, have a round cross-section, small branches, minimal defects such as knots or insect damage, and have a sufficient girth (>25 cm) and length (>2.4 m) (James 2001). These high quality requirements combined with the high degree of defect and the characteristic branching form of species harvested in Queensland explain the low mean sawlog recovery of 41.4% found in this study. It also highlights that there is an opportunity to utilize for bioenergy those portions of felled trees that are defective, are too small in diameter and/or too short in length to be utilized as sawlog and hence would otherwise be left on the forest floor. In NSW, Australia, where the estimated mean proportion of aboveground tree biomass utilized as commercial log can accounts for 64%, the portions that do not meet high value veneer or sawlog quality have in the past been harvested for low value uses such as pulp and posts (Ximenes et al. 2008). In Queensland markets for these lower grade components are currently limited or do not exist and about 22.6% of whole tree biomass is therefore potentially available for bioenergy or for other emerging markets such as veneer processing using a spindleless lathe (McGavin et al. 2014).

The proportion of whole tree biomass able to be harvested as commercial log when pulpwood is recovered has been reported to be as high as 70% for *Eucalyptus obliqua* in NSW (Ximenes et al. 2008). This suggests that more biomass for bioenergy can be sourced from forests in Queensland if such a proportion of tree biomass was harvested. Species with comparable growth habits do occur in Queensland, such as *Eucalyptus grandis* and *Eucalyptus saligna* (BVG 8a), and are likely to yield a similar high proportion of commercial log. However, with such species, the top section of the stem is likely to be straight and comparatively free of knots and thus to still meet specifications for veneer, a more valuable product than biomass for bioenergy (McGavin et al. 2014).

The future biomass production of sustainably managed private native forests is anticipated to increase. This potential is evident when we compare current productivity of these forests with similar native forests found on state owned forests in Queensland that have in the past been sustainably managed for timber production (Ngugi et al. 2014). Using the total aboveground biomass recorded before harvest in this study, the estimated biomass values from similar BVG in state managed forests (Ngugi et al. 2014) are between 2 to 7 times higher. For example, the mean stand biomass of spotted gum forests (BVG 10b) in state managed forests is twice as much, that of moist open forests dominated by *Eucalyptus pilularis* (8b) is seven times higher and that of wet tall open forests (8a) is five times higher than that reported for equivalent BVG in private native forests in this study. This difference is largely the result of past disturbance such as fires and vegetation management history such as "high grading" forest harvesting and clearing for grazing purposes in private land ownership (Ryan and Taylor 2006). Ryan and Taylor (2006), have demonstrated that application of silvicultural treatment and sustainable wood harvesting of these forests has the potential to enhance rates of biomass accumulation by concentrating biomass growth on larger trees instead of many small trees. Additionally, this practice enabled development of a ground layer of grass cover needed for soil protection and grazing, ensuring that these forests continue to provide environmental benefits and economic returns far into the future.

This study has demonstrated that private native forest management in SEQ has the potential to produce a very large amount of biomass for bioenergy (13,575,000 t). Based on biomass distribution mapping shown in Fig. 2, over 8 million tonnes of biomass are currently found in local government areas in the northern part of the bioregion around the towns of Bundaberg, Miriam Vale, Maryborough and Gympie. This biomass could make a significant ongoing contribution to reducing Australia's greenhouse gas emissions by displacing the use of coal in the generation of electricity for plants that use technology which is compatible with co-firing woody biomass (McEvilly et al. 2011). In general terms, the available biomass for bioenergy in SEQ is within 200 km to the nearest major coal-fired electricity generation facility which include Tarong (near Kingaroy), Callide (near Biloela), Millmerran, Gladstone and Stanwell (near Rockhampton) (McEvilly et al. 2011). Put into perspective, the biomass resource in the bioregion has the capacity to produce 13,575,000 MW hours of heat energy (using conversion of one tonne of wood biomass for one megawatt hour of heat (Shelly 2010)). This energy can supply electricity to a city of 50,000 households such as Gladstone (average household electricity consumption in Australia in 2014 was 5817 kWh·yr.$^{-1}$ (Acil Allen Consulting 2015)) for approximately 47 years.

Alternatively, woody biomass resource could provide a valuable feedstock for producing biofuels such as aviation fuels (Booth et al. 2014; Murphy et al. 2015) and to potential biofuel generators within SEQ such as the Northern Oil at Gladstone. Additionally, the resource could supply wood pellet for export to distributors such as Altus Renewables at Tuan in Queensland. The demand for biomass is also set to increase in order to meet the "biobased" diesel mandate that requires that by July 2018, 0.5% of all diesel fuel sold in Queensland should be "biobased" (Advance Queensland 2016). The emerging biomass for bioenergy industry creates an additional revenue stream offering the economic incentive necessary for private native forest landowners to undertake silvicultural treatments. In addition, a rejuvenated forest industry is likely to also benefit the community by providing employment opportunities and income, displacing energy intense and non-renewable building materials (such as steel and concrete) (Moroni 2012; Smyth et al. 2017) and by improving the condition of the forests for other environmental outcomes (Commonwealth of Australia, 2015a, b).

Community concerns about potential negative environmental effects are possibly the largest barrier to establishing a native forest-based biomass harvesting industry in Australia (Rothe et al. 2015). Harvesting timber from native forests, in particular harvesting of low grade residues, has been a point of contention within parts of the Australian community for many decades, for example in Tasmania (Routley and Plumwood 1986; Ulrik 2012; Rothe et al. 2015). Instances of questionable practices where tree harvesting has been particularly intense and the impacts (particularly of animal habitat, water quality and aesthetics) obvious and lasting have contributed to this concern (Routley and Plumwood 1986). Concern about the negative environmental impacts of native forest logging has been strongest where forests are in public ownership, have limited history of previous logging, and where residues are being exported for low value use (such as paper manufacture), however it has influenced political and community attitudes to management and land clearing of native forests more generally (Routley and Plumwood 1986; Ulrik 2012; Bradshaw 2012; Macintosh 2013).

There are a number of factors mitigating against the risk of environmental harm in relation to biomass harvesting from private native forests in Queensland. First, estimates from biomass proportion studies discussed in this study (Ximenes et al. 2008) suggest that approximately 36% of felled tree biomass would be retained on-site and on the forest floor for enhancing long-term soil productivity, water quality, and site-level biodiversity values. This proportion suggest a higher on-site biomass retention compared to the estimated mean proportion of total aboveground biomass as forest floor coarse wood debris in Australian native forests that ranges from 16% in tall open forests to 18% in open forests (Woldendorp and Keenan 2005).

Secondly, tree harvesting practices within private native forests are strictly regulated by the Code of practice (DNRM 2014), to protect habitat, soil and water values under Queensland's Vegetation Management Act (QLD VM Act 1999). Thirdly, for an energy producer to gain credits under Australia's Federal Renewable Energy Legislation (Commonwealth of Australia, 2015a, b) for substituting fossil fuels with native forest biomass, they must demonstrate that the biomass is from an operation that is: primarily geared to produce higher-value products such as sawlogs (including thinnings and coppice) and is carried out in accordance with ecologically sustainable forest management principles approved and certified under relevant Commonwealth, State or Territory planning and approval processes. This requirement is generally considered to be as a minimum the Australian Forestry Standard (AFS) or the Forestry Stewardship Council (FSC) certification (Department of Agriculture 2015).

Nevertheless, the removal of poorly formed individual trees for biomass production, and removal of 64% of the bole section of trees is likely to affect long-term availability of coarse wood material on the forest floor as observed in forests harvested for bioenergy supply for a period of over a decade in the United States of America (Briedis et al. 2011; Klockow et al. 2013). Under the current forest practice in Queensland, Australia, poorly formed individual trees not suitable for sawlog harvest, rotten heartwood or knotted or damaged large diameter sized sections of felled trees and the crown section deemed unsuitable for sawlog, provide necessary food and habitat for fauna species (Eyre et al. 2015) and fuelwood (West et al. 2008). Normally, when these poorly formed standing trees fall down they become part of the large coarse woody material on the forest floor (Eyre et al. 2015). Although the present code (DNRM 2014) only prescribes the retention of standing habitat trees, if an industry developed around the harvesting and use of poorly formed trees, the Code may need to be extended to provide guidelines for the retention of snags (standing dead trees) and coarse wood material on the forest floor for fauna habitat functions (Woldendorp and Keenan 2005).

## Conclusion

This study has provided a point-in-time stock-take of potentially available biomass for bioenergy in privately owned native forests in the Southeast Queensland bioregion estimated at 13,575,000 t. The study has also provided an estimation methodology and maps showing the 2014 extent and location of these forests and estimates of the amount of biomass that can be sourced from each local government area within the bioregion. These estimates indicate the potential capacity of private native forest and are useful for informing policy and potential development of a wood based renewable bioenergy industry. Developing a bioenergy market for biomass from these forests could provide the motivation and financial means for landowners to adopt silvicultural management necessary to promote growth of the retained forests and hence ensure sustainable supply of ecological and economic benefits into the future. However, more detailed research on the long-term availability of 'sustainable' biomass over coming decades to support investment in bioenergy (Booth et al. 2014; Murphy et al. 2015), economic viability of a biomass for bioenergy industry (Hayward et al. 2015), sustainable biomass retention proportion for environmental protection including coarse wood material for fauna habitat as well as energy generated from burning different types of tree species is needed.

### Abbreviations

ABARE: Australian Bureau of Agricultural and Resource Economics; ABBA: Australian Biomass for Bioenergy Assessment; AFS: Australian Forestry Standard; AGB: Aboveground biomass; BVG: Broad Vegetation Groups; DAF: Department of Agriculture and Fisheries; DCDB: Digital cadastral database; DEM-H: Digital Elevation Model- Hydrological; DPI, NSW: Department of Primary Industries, New South Wales; FH: Freehold land; FPC14: Foliage projective cover 2014; FSC: Forestry Stewardship Council; HVR: High value regrowth; NF: Native forests; NFPP: Native forest permanent sample plots; NSW: New South Wales; PFSQ: Private Forestry Service Queensland; QH: Queensland Herbarium; RE: Regional ecosystem; Remcov15: Remnant regional ecosystem cover 2015; SEQ: Southeast Queensland; SLATS: Statewide landcover and trees study; SRTM: Shuttle radar topography mission

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### Availability of data and materials

All data used in this study can be obtained through data share agreement with the Private Forestry Service Queensland and the Queensland Department of Agriculture and Fisheries.

### Authors' contributions

PN, MRN, JN conceived the research and SR, TL contributed to design and supplied data; MRN, MM analysed tree data; JL analysed spatial data; MRN wrote the draft manuscript; JN, SR, TL, JL, PN, edited and improved the manuscript; All authors read and approved the final manuscript.

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

### Author details

[1]Department of Environment and Science, Queensland Herbarium, Mt Coot-tha Road, Toowong, Qld 4066, Australia. [2]Private Forestry Service Queensland, 8 Fraser Rd, Gympie, Qld 4570, Australia. [3]Department of Agriculture and Fisheries, University of Sunshine Coast, Sippy Downs, Qld 4556, Australia. [4]Department of Environment and Science, Soil and Land Resources, 41 Boggo Road, Dutton Park, Qld 4102, Australia. [5]University of Queensland, St Lucia, Qld 4072, Australia.

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