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Rethinking forest carbon assessments to account for policy institutions

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There has been extensive debate about whether the sustainable use of forests (forest management aimed at producing a sustainable yield of timber or other products) results in superior climate outcomes to conservation (maintenance or enhancement of conservation values without commercial harvesting)[1–8]. Most of the relevant research has relied on consequential life-cycle assessment (LCA), with the results tending to show that sustainable use has lower net greenhouse-gas (GHG) emissions than conservation in the long term[1–5]. However, the literature cautions that results are sensitive to forest- and market-related contextual factors: the carbon density of the forests, silvicultural and wood processing practices, and the extent to which wood products and forest bioenergy displace carbon-intensive alternatives. Depending on these issues, conservation can be better for the climate than sustainable use[1,6–8]. Policy institutions are another key contextual factor but, so far, they have largely been ignored[1–6]. Using a case study on the Southern Forestry Region (SFR) of New South Wales (NSW), Australia, we show how policy institutions can affect the assessed outcomes from alternative forest management strategies. Our results highlight the need for greater attention to be paid to policy institutions in forest carbon research.

Institutions are generally defined as norms that structure human behaviour and social interactions[9,10]. In the current context, the phrase 'policy institutions' is used to refer to the rules and procedures adopted by governments and inter-governmental organizations concerning GHG mitigation and accounting.

Borrowing from LCA nomenclature, we classify relevant policy institutions as macro, consequential or attributional[11–13]. Macro policy institutions are those concerning policy objectives and principles. Consequential policy institutions are those that affect substantive outcomes; they provide incentives (inducements, penalties or information) for policy actors to behave in ways that affect emissions and removals. Attributional policy institutions are those that assign responsibility for emissions and removals between jurisdictions and other relevant actors (Table 1).

An example of a policy instrument that combines consequential and attributional institutions is a cap-and-trade emissions trading scheme. Owing to the cap on emissions (a consequential policy institution), if forest management activities result in an increase in emissions covered by the scheme—for example, if conservation results in substitution by non-wood products and the facilities that produce these products are subject to the scheme—the net emission outcome from the scheme as a whole should be unaffected. There is an institutional requirement that the increase be offset by a proportional decrease in emissions, or increase in removals, elsewhere, which works via the scheme's incentives: a restricted supply of emission permits, a market in which permits and offsets are exchanged, and compliance penalties. In addition to these consequential elements, emissions trading schemes rely on attributional policy institutions to assign responsibility for emissions and removals between parties and set rules for measurement, verification and reporting. In isolation, these institutions do not affect the net emission outcome but they are required for the scheme to function.

The nature of these policy institutions is widely understood in policy circles but, so far, their impacts have not been fully reflected in forest carbon research. Studies that have sought to evaluate the relative GHG benefits of alternative forest management strategies have typically used LCA methods to track carbon stock changes under corresponding sustainable use and conservation scenarios from the on-site forest, harvested wood products and landfill carbon pools, and avoided emissions through product substitution and fossil fuel displacement[1–8,14–16]. Whereas the coverage of sources and sinks has usually been comprehensive, most studies have overlooked the effects of policy institutions.

To illustrate the relevance of policy institutions, we completed an LCA on the SFR; a commercial public native forest estate covering almost 430,000 ha comprising a mix of *Eucalyptus*- and *Corymbia*-dominated forest types. Most of the estate is regrowth and mature forest and, over the past decade, roundwood removals consisted of ~380,000 green tonnes yr^{-1} of pulplogs and ~150,000 $m^3 yr^{-1}$ of sawlogs[17,18]. The products derived from the sawlogs consist, in relatively equal proportions, of dry and dressed timber (mainly for floorboards, decking and panelling), green structural timber (mainly for framing), and fencing and landscaping products, which are sold almost exclusively in domestic markets[14,17,18]. The pulplogs are processed at a single woodchip mill, before being exported to Japan for paper production. No electricity is currently produced from forest biomass.

The LCA compared the GHG outcomes of conservation relative to a sustainable use reference case. Eight scenario sets were devised around three main policy institution assumptions: basic, global and national (Table 2). The basic scenarios assessed global net emissions outcomes using 'typical' forest LCA methods, including that emissions-intensive non-wood substitutes replace foregone sawnwood products, forest bioenergy (where relevant) displaces coal-fired generation throughout the 100-year projection period and policy institutions are not accounted for[1–8,14–16]. The global scenarios assessed global net emissions outcomes, having regard to applicable macro and consequential policy institutions. The national scenarios assessed impacts on Australia's net emissions, having regard to applicable macro, consequential and attributional policy institutions.

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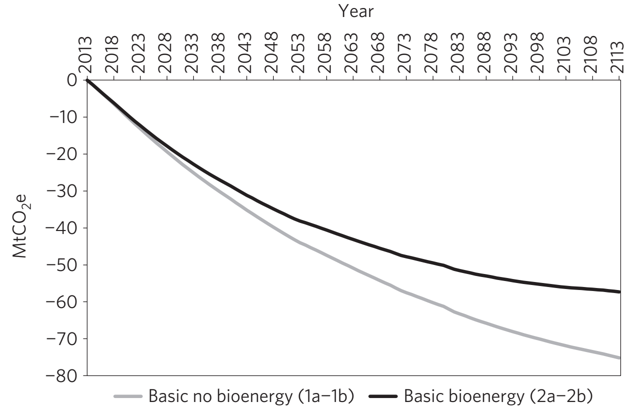

Figure 1 | Basic scenarios—difference between the sustainable use reference case and the conservation scenario as cumulative net GHG emissions. Net emissions were calculated as the net flux difference (emissions less removals) between the sustainable use reference case and the conservation scenario. Positive net emissions occur when net emissions in the conservation scenario are greater than those in the sustainable use reference case; negative net emissions occur when net emissions in the conservation scenario are less than those in the sustainable use reference case (abatement).

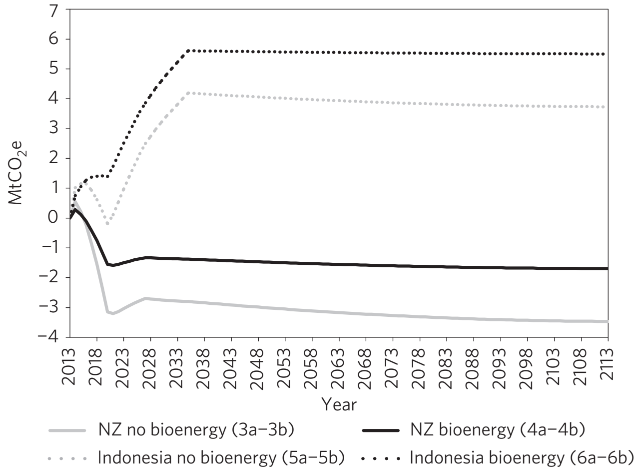

Figure 2 | Global scenarios—difference between the sustainable use reference case and the conservation scenario as cumulative net GHG emissions. Net emissions were calculated as the net flux difference (emissions less removals) between the sustainable use reference case and the conservation scenario. Positive net emissions occur when net emissions in the conservation scenario are greater than those in the sustainable use reference case; negative net emissions occur when net emissions in the conservation scenario are less than those in the sustainable use reference case (abatement).

The results of the basic scenarios suggest conservation will produce significantly better GHG outcomes than sustainable use over the projection period, with cumulative abatement of 57–75 Mt of CO_2-equivalent emissions ($MtCO_2e$; Fig. 1). The greater emissions from the sustainable use scenario are attributable to the high proportion of biomass left on the forest floor after harvesting and the low percentage of roundwood assigned to long-lived wood products.

The outcomes of the global scenarios are radically different. Depending on where sawnwood production is displaced, the global net emissions outcome from conservation ranged between a reduction in emissions of 1.7–3.5 $MtCO_2e$ and an increase in emissions of 3.7–5.5 $MtCO_2e$ (Fig. 2).

These differences are not an artefact of accounting; they are a product of macro and consequential policy institutions, the most important of which is the obligation under international law for Australia to keep its national net emissions within a specified limit (its quantified emission limitation or reduction objective). We assumed Australia abides by this obligation and continues to adhere to similar international commitments throughout the projection period (consistent with the macro objective to avoid dangerous climate change).

Owing to the cap on Australia's net emissions, all domestic emissions and removals, including those from and associated with the management of the SFR, should have no impact on the global net emission outcome. The cap serves as both a floor and ceiling on net national emissions and, in doing so, sets Australia's contribution (as defined by international law) to the global outcome. The main qualification to this is that net emissions from the SFR could be excluded from the national cap by virtue of the forest management rules. For example, under the Kyoto Protocol, credits from forest management are limited to 3.5% of a party's base year emissions[19]. It was assumed that this limit does not bind and that forest management credits from the SFR are not excluded by any future rules.

With national net emissions capped, the main determinants of the global GHG outcomes are the extent to which emissions and removals leak into other jurisdictions as a consequence of the cessation of harvesting and whether those jurisdictions have policy institutions that constrain or otherwise affect emissions. To capture the uncertainty associated with these issues, we developed two subscenario sets. The first assumed all imported substitute products are derived from New Zealand plantations (NZ scenarios), Australia's traditional principal supplier of sawnwood imports[20]. New Zealand has pledged to cap its emissions to 2020 and we assumed that it both adheres to this pledge and adopts emissions constraints beyond 2020. The second set assumed all imported substitute products are derived from primary Indonesian rainforest where, initially, there are no emission constraints (Indonesia scenarios). We assumed that it takes until 2035 for Indonesia to adopt comprehensive emission caps that apply to its net forest and fossil fuel emissions. In both cases, we assumed the substitute woodchips were sourced from Vietnamese eucalypt plantations and that it too adopts emission limits in 2035.

The positive climate outcome from conservation in the NZ scenarios (net abatement of 1.7–3.5 $MtCO_2e$) is mainly attributable to assumed reforestation in Vietnam for woodchip production and a reduction in international shipping emissions associated with the transport of woodchips to Japan. The negative climate outcome from conservation in the Indonesia scenarios (net emissions of 3.7–5.5 $MtCO_2e$) is due to the logging of the Indonesian rainforests and an increase in uncapped fossil fuel emissions until 2035 from wood processing and transportation.

Australia's primary international mitigation obligation is not to reduce global emissions; it is to contribute to the avoidance of dangerous climate change by ensuring its net national emissions stay within its cap. Reflecting this, and the consequent likely needs of domestic policymakers, the national scenarios quantified the impacts of the alternative SFR management strategies on Australia's net emissions.

With the scope of inquiry confined to impacts on national net emissions, conservation of the SFR generated 79–85 $MtCO_2e$ of cumulative abatement over the projection period relative to the sustainable use reference case, 10–21 $MtCO_2e$ above the equivalent results from the basic scenarios (Fig. 3).

The difference in the results between the basic and national scenarios is a product of two main institutional factors. The first (attributional) is the international greenhouse accounting rules, which define Australia's net emissions using a production approach, whereby it is generally responsible only for those emissions that

Table 1 | Types of policy institutions relevant to mitigation strategies for forests.

Institution type	Main institutions	Relevance	Import of institution in case study
Macro	International and domestic climate policy objectives and principles	Set policy objectives, the frame through which policy options are assessed and the principles for determining what emissions and removals matter in policy processes.	Affect long-term assumptions about consequential and attributional policy institutions, and ensure impacts on both global and national net emissions are relevant in the assessment of forest management options.
Consequential	International mitigation obligations	Require countries to abate emissions, increase removals and/or keep their national net emissions within prescribed limits (or caps).	Caps national net emissions, meaning activities that affect national emissions and removals should not change the net emissions outcome.
	Domestic policy instruments	Provide incentives to modify domestic activities that affect emissions and removals.	Determine or influence the nature of the substitutes for displaced wood products and their emissions-intensity, and how they change over time.
Attributional	International greenhouse accounting rules	Define extent of responsibility for national emissions and removals (those occurring in or linked to the jurisdiction) and the rules according to which these emissions and removals are measured, verified and reported.	International leakage effects are excluded from scope of attributional LCA.
	Domestic greenhouse accounting practices	Determine detailed methods and procedures for measuring, verifying and reporting national emissions and removals.	Determine methods for estimating fluxes from on-site forest, harvested wood products and landfill carbon pools, and avoided emissions through product substitution and fossil fuel displacement.

Table 2 | Scenario descriptions.

No.	Scenario name	Bioenergy (B) or no bioenergy (NB)	Assumed source of imported substitutes	Assumed source of substitute woodchips
1a	Basic no bioenergy: sustainable use	NB	–	–
1b	Basic no bioenergy: conservation	NB	–	–
2a	Basic bioenergy: sustainable use	B	–	–
2b	Basic bioenergy: conservation	B	–	–
3a	Global NZ no bioenergy: sustainable use	NB	New Zealand	Vietnam
3b	Global NZ no bioenergy: conservation	NB	New Zealand	Vietnam
4a	Global NZ bioenergy: sustainable use	B	New Zealand	Vietnam
4b	Global NZ bioenergy: conservation	B	New Zealand	Vietnam
5a	Global Indonesia no bioenergy: sustainable use	NB	Indonesia	Vietnam
5b	Global Indonesia no bioenergy: conservation	NB	Indonesia	Vietnam
6a	Global Indonesia bioenergy: sustainable use	B	Indonesia	Vietnam
6b	Global Indonesia bioenergy: conservation	B	Indonesia	Vietnam
7a	National no bioenergy: sustainable use	NB	–	–
7b	National no bioenergy: conservation	NB	–	–
8a	National bioenergy: sustainable use	B	–	–
8b	National bioenergy: conservation	B	–	–

occur within its sovereign territory[19,21]. It is not liable for emissions, or able to count removals, that occur in other countries as a consequence of SFR management decisions (there are exceptions, including in relation to harvested wood products; Supplementary Information). There are also detailed accounting rules concerning forest management, the most notable of which require emissions and removals from the forests of the SFR to be counted (subject to the 3.5% limit) and effectively exclude emissions from wildfires on the basis that they are non-anthropogenic[19].

If harvesting ceased in the SFR, most of the substitutes for the foregone sawnwood products are likely to be imported or derived from domestic plantations[22–24]. Owing to the international accounting rules, emissions embodied in imports were excluded[19], and products derived from domestic plantations were assumed to be less emissions-intensive than non-wood substitutes. The cessation of woodchip exports to Japan would probably result in substitution by plantation-derived chips from Southeast Asia[23,24]. Again, the emissions associated with these foreign products were excluded from the national scenarios because they do not count towards Australia's total.

The second factor that explains the difference between the basic and national scenarios is the assumptions made regarding macro and consequential policy institutions. There is bi-partisan agreement in Australia that the overriding climate policy objective should be to meet international mitigation obligations at least cost[25]. The adoption of this objective means that it is unlikely that a forest mitigation strategy would be pursued in isolation. Policy instruments will be designed to capture abatement across the economy. To account for this, we assumed that a combination of unspecified policy instruments result in a gradual decline in

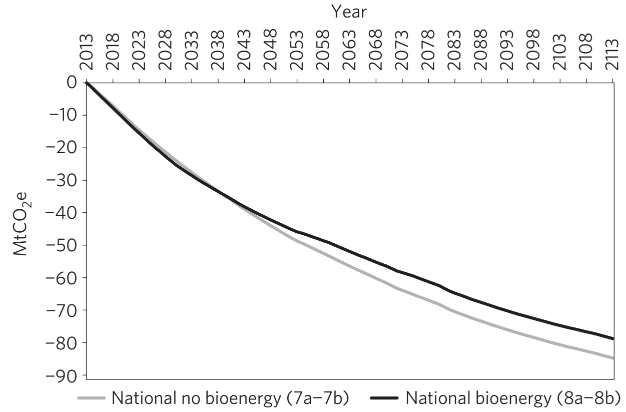

Figure 3 | National scenarios—difference between the sustainable use reference case and the conservation scenario as cumulative net GHG emissions. Net emissions were calculated as the net flux difference (emissions less removals) between the sustainable use reference case and the conservation scenario. Positive net emissions occur when net emissions in the conservation scenario are greater than those in the sustainable use reference case; negative net emissions occur when net emissions in the conservation scenario are less than those in the sustainable use reference case (abatement).

applicable product and fossil fuel displacement factors over the projection period.

The other important domestic consequential policy institution assumption was that Australia's renewable portfolio standard, the Large-scale Renewable Energy Target (LRET), remains in place. The LRET requires a prescribed amount of electricity to be obtained from renewables each year through to 2030. The presence of the LRET means that bioenergy generation in the SFR will not normally increase renewable energy or lower emissions. If the generator participates in the LRET, it will merely displace other forms of renewable generation. We accounted for this in the national bioenergy scenarios by assuming bioenergy generation displaces other renewable generators until 2030, after which it displaces emissions-intensive coal and gas until late in the projection period.

The results of the SFR case study highlight the extent to which policy institutions matter in forest LCAs. Institutional assumptions can substantially alter the assessed outcomes of forest management strategies. Incorporating institutional factors into forest LCAs adds complexity and uncertainty, including about institutional compliance and longevity. However, it is necessary to ensure they accurately capture relevant climate impacts and provide outputs that are suitable for policy purposes.

Methods

Methods and any associated references are available in the online version of the paper.

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References

1. Bustamente, M. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) Ch. 11 (IPCC, Cambridge Univ. Press, 2014).
2. Nabuurs, G. J. *et al.* in *Climate Change 2007: Mitigation* (eds Metz, B. *et al.*) Ch. 9 (IPCC, Cambridge Univ. Press, 2007).
3. Perez-Garcia, J., Lippke, B., Comnick, J. & Manriquez, C. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. *Wood Fibre Sci.* **37,** 140–148 (2005).
4. Sathre, R. & O'Connor, J. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environ. Sci. Policy* **13,** 104–114 (2010).
5. Lippke, B. *et al.* Life cycle impacts of forest management and wood utilization on carbon mitigation: Knowns and unknowns. *Carbon Manage.* **2,** 303–333 (2011).
6. Lamers, P. & Junginger, M. The 'debt' is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels Bioprod. Biorefin.* **7,** 373–385 (2013).
7. Zanchi, G., Pena, N. & Bird, N. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *Glob. Change Biol.* **4,** 761–772 (2012).
8. Mitchell, S. R., Harmon, M. E. & O'Connell, K. Carbon debt and carbon sequestration parity in forest bioenergy production. *Glob. Change Biol.* **4,** 818–827 (2012).
9. Powell, W. W. & DiMaggio, P. J. (eds) *The New Institutionalism in Organizational Analysis* (Univ. Chicago Press, 1991).
10. Hodgson, G. M. What are institutions? *J. Econ. Issues* **40,** 1–25 (2006).
11. Sandén, B. A. & Karlström, M. Positive and negative feedback in consequential life-cycle assessment. *J. Clean. Prod.* **15,** 1469–1481 (2007).
12. Finnveden, G. *et al.* Recent developments in life cycle assessment. *J. Environ. Manage.* **91,** 1–21 (2009).
13. Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge Univ. Press, 1990).
14. Ximenes, F., George, B., Cowie, A., Williams, J. & Kelly, G. Greenhouse gas balance of native forests in New South Wales, Australia. *Forests* **3,** 653–683 (2012).
15. Oliver, C. D., Nassar, N. T., Lippke, B. & McCarter, J. B. Carbon, fossil fuel, and biodiversity mitigation with wood and forests. *J. Sustain. For.* **33,** 248–275 (2014).
16. Lamers, P., Junginger, M., Dymond, C. C. & Faaij, A. Damaged forests provide an opportunity to mitigate climate change. *Glob. Change Biol.* **6,** 44–60 (2014).
17. *NSW Forest Agreements Implementation Reports 1999 to 2010* (NSW Government, 2004 to 2011).
18. *Integrated Forestry Operations Approval Annual Reports, Eden and Southern RFA Areas 2001 to 2013* (Forestry Corporation of NSW, 2001 to 2013).
19. Hiraishi, T. *et al.* (eds) *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol* (IPCC, 2014).
20. Australian Bureau of Agricultural and Resource Economics and Sciences *Australian Forest and Wood Products Statistics* (Commonwealth of Australia, 2014).
21. Eggleston, S. *et al. 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Institute for Global Environmental Strategies, 2006).
22. *Sawn Timber in Australia 2012–2026* (BIS Shrapnel, 2012).
23. Whittle, L., Berry, P. & Heyhoe, E. *Leakage from Avoided Clearing and Harvesting of Native Forests under the CFI: A Quantitative Assessment* (Commonwealth of Australia, 2013).
24. Macintosh, A. *The Australian Native Forest Sector: Causes of the Decline and Prospects for the Future* (The Australia Institute, 2013).
25. Australian Government *Emissions Reduction Fund White Paper* (Commonwealth of Australia, 2014).

Author contributions

A.M. designed the research, analysed data, created the models and drafted and revised the paper. H.K. assisted with data analysis and drafting and revising the paper. D.L. helped draft and revise the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.M.

Competing financial interests

A.M. is the Chair of the Australian Emissions Reduction Assurance Committee, a statutory body responsible for overseeing carbon offset methods developed for the purpose of the Australian Government's Emissions Reduction Fund. The content of the letter reflects his personal views, not those of the Committee or the Australian Government.

Methods

Introduction. For each of the eight scenario sets, we modelled emissions and removals from the six relevant sinks and sources: on-site forest carbon; harvested wood products; landfill; fossil fuel emissions from forest management, transport, and wood processing; emissions from product substitution; and net avoided emissions through bioenergy production. Supplementary Tables 1 and 2 summarize the coverage of the sinks and sources.

On-site forest carbon. The Southern Forestry Region (SFR) consists of a mix of forest types dominated by *Eucalyptus* and *Corymbia* spp., including *C. maculata*, *E. muelleriana*, *E. pilularis*, *E. sieberi*, *E. obliqua*, *E. fastigata*, *E. cypellocarpa* and *E. delegatensis*[14,26–28]. Most of the estate is regrowth and mature forest, with only a small fraction (0.5%) being high conservation value old growth (Supplementary Fig. 1)[29,30].

Mirroring the Australian Government's approach to modelling public native forests[31], the SFR forest estate was modelled using the Tier 2 capabilities of FullCAM (version 3.30.1; ref. 32). For modelling purposes, the region was divided into its three management sub-regions (South Coast, Tumut and Eden) and representative FullCAM forest plots were devised for each sub-region. Details of the gross area and net harvestable area of the sub-regions are provided in Supplementary Table 3 (refs 26–28).

The representative FullCAM plots were based on the 'medium dense eucalypt forest' and 'tall dense eucalypt forest' plots used in the Australian Government's public native forest model[31]. The medium dense eucalypt forest plot provided the basis for the South Coast and Eden plots, the tall dense eucalypt forest plot provided the basis for the Tumut plots. Adjustments were made to these base plots to account for the assumed silviculture practices, basic density and above-ground biomass yields in the SFR.

Silviculture practice assumptions. Eighteen representative plots were developed that broadly reflect current silvicultural practices and forest types in the SFR (Supplementary Table 4)[14,26–30]. For the South Coast, we assumed 64% of the estate was harvested by way of modified single tree selection (STS), with the remainder subject to Australian group selection (AGS; ref. 26). Based on state forestry agency data, 12% of the estate was assumed to be thinned at 30 years[26]. For Tumut, we divided the net harvestable area into two broad forest types—alpine ash and mountain hardwood—and assumed harvesting in both was by way of STS or AGS. No thinning was assumed to occur in the Tumut sub-region[27]. To reflect the impact of environmental restrictions, in each rotation, we assumed 10% of the net harvestable area in the South Coast and Tumut sub-regions was not harvested[33]. For Eden, the estate was broken into regrowth and older multi-aged forest, with the latter comprising 15% of the sub-region[28]. The majority of existing multi-age forest was assumed to be harvested over the first two decades of the projection period, thereby converting it into managed regrowth. Two-thirds of all regrowth forest was assumed to be thinned at 30 years, with a subsequent regeneration harvest at 70 years. The remainder was assumed to be subject to a single regeneration harvest at 60 years.

All plots in each sub-region were assumed to have the same slash proportions (Supplementary Table 5)[31,34]. However, the proportion of above-ground biomass assigned to slash was assumed to be lower in the bioenergy scenarios to reflect the use of sub-pulp grade logs for bioenergy. In the bioenergy scenarios, all branches, bark, leaves and roots were assumed to be left on-site to maintain soil fertility[14,35,36].

Basic density. The basic densities in the base plots were adjusted to reflect the forest types in the sub-regions (Supplementary Table 6)[14,31,34,37]. All other parameters, including yield allocations to tree components, carbon and turnover percentages, and debris breakdown percentages, were assumed to be the same as those in the relevant base plot.

Above-ground biomass yields. The above-ground biomass yields in each plot were modelled using the equation:[38,39]

$$\mathrm{ABY} = \alpha[1 - \mathrm{e}^{(-\beta * \mathrm{Age})}]^{\gamma} \qquad (1)$$

ABY is the above-ground biomass yield (bone dry metric tonnes), Age is the stand age in years, α is the maximum attainable above-ground biomass (upper asymptote of the curve) and β and γ determine the shape of the curve (growth rate to the asymptote). The standard parameters for α, β and γ used in the plots are provided in Supplementary Table 7. Adjustments were made to these parameters to account for the impact of thinning (increased growth rates of residual trees and impeded new growth).

The parameters for the plots in Supplementary Table 7 were developed iteratively to ensure the modelled sub-region roundwood removals matched sustainable yield forecasts published by the Forestry Corporation of New South Wales (NSW; refs 26–28). The published sustainable yield forecasts do not cover all log categories. To address this, we used historical data to calculate a ratio between the published log categories and total roundwood removals[17,18], and then applied the ratio to the forecast yields. The resulting correlation between the modelled roundwood removals and adjusted sustainable yield forecasts is shown in Supplementary Fig. 2.

Harvested wood products and landfill. Harvested wood products and landfill carbon stocks and emissions were modelled using an integrated version of the Australian Government's models[31,40]. The inputs for the integrated product/landfill model were derived from the FullCAM outputs.

Over the period 2003–2011, 71% of roundwood removals from the SFR were pulplogs, 26% were sawlogs and 3% were other logs (for example, poles, girders, landscaping and sleeper logs; Supplementary Fig. 3)[17,18]. In the no bioenergy scenarios, these proportions were used as the basis for assigning roundwood removal outputs to log categories. In the bioenergy scenarios, we assumed sub-pulp grade logs (which would otherwise have been left as slash) and 50% of pulplogs were used for bioenergy[14,35,36]. The proportion of total roundwood removals (including removals for bioenergy) assigned to each log type is provided in Supplementary Table 8.

The processing destination fractions for logs and wood waste were derived from the Australian Government's harvested wood products model, with adjustments made to account for regional industry characteristics (Supplementary Data File)[31,40]. The destination fractions provided the basis from which end-products were assigned to the product pools contained in the harvested wood products model (Supplementary Table 9). The maximum age and decay rates for the product pools are summarized in Supplementary Table 10[31,40]. Exported wood chips were not modelled within the Australian Government's harvested wood product model paper pool (pool 1). Consistent with the international accounting rules, they were modelled using the IPCC first-order decay function, with a paper default half-life of two years[19]. The destination fractions for losses from the product pools are provided in the Supplementary Data File.

The Australian Government's landfill model is based on the IPCC Tier 2 first-order decay (FOD) model[21,31]. The key parameters of the model are the fraction of degradable organic carbon in each individual waste type (DOC); the rate of decay assumed for each individual waste type (decay function 'k'); the fraction of degradable organic carbon that dissimilates through the life of the waste type (DOCf); the methane correction factor (MCF); the methane recovery rate (proportion of methane captured for flaring and energy generation); and the oxidation factor (the proportion of methane that oxidizes before reaching the surface of the landfill)[21,31]. The inputs for the landfill model were derived from the HWP model in tonnes of carbon (tC), making the DOC value redundant. Details of the remaining parameters are provided in Supplementary Table 11.

Fossil fuel emissions from transport, processing and management. The fossil fuel emissions associated with harvesting, hauling, processing and transporting wood and waste products to relevant markets, and the fossil fuel emissions associated with forest establishment and management, were calculated using data from industry and government sources[41–43]. Details of the energy and emission factors, and transport distance assumptions are provided in the Supplementary Data File.

Product substitution. Since the mid-1990s, hardwood log production from NSW public native forests has fallen by 50% (Supplementary Fig. 4)[44–48]. Similar trends have been seen across Australia, with falls in native hardwood log production being experienced in all relevant states[20,22,24,49]. The decline in production, both in NSW and Australia-wide, is attributable to a combination of market-related factors—particularly weak demand growth and increased competition in domestic solid wood product markets, falling export woodchip prices, and increased harvesting and haulage costs—and regulatory changes that resulted in the expansion of the national reserve system at the expense of the commercial public native forest estate[22,24]. In NSW, since the mid-1990s, 1.3 Mha (43%) of the commercial public native forest estate has been transferred to the reserve system[24].

The decrease in log supply has not been accompanied by increases in real prices of relevant native hardwood products. Native hardwoods have been largely replaced in domestic solid wood product markets by sawnwood from domestic coniferous plantations and domestic and imported wood-based panels (Supplementary Fig. 5)[22,24,49]. The competition from these substitutes, and foreign sawnwood suppliers, have kept real prices of relevant native hardwood structural and appearance-grade flooring products relatively stable for the past 10–15 years (Supplementary Figs 6 and 7)[20,22,24,50].

We assumed for current purposes that the cessation of supply of sawnwood products from the SFR could result in substitution from five possible sources: domestic native wood products, domestic plantation sawnwood products, domestic plantation-derived wood-based panels, domestic non-wood products and imported products.

In the basic scenarios, we ignored the market dynamics in relevant solid wood product markets and, consistent with other forest-related LCAs, simply assumed substitution was wholly through non-wood products[4–6,14,15]. A constant product displacement factor of 2.1 tC (every 1 tonne of carbon in a sawnwood product foregone through conservation results in 2.1 tC of emissions from the production of the relevant substitute) was then applied to calculate leakage in the conservation scenarios[4].

As the history summarized in Supplementary Figs 4–7 suggests, both market and institutional factors make it unlikely that, in the event that harvesting ceased in the SFR, there would be a high rate of leakage into domestically produced carbon-intensive substitutes. A high rate of leakage into other domestic native forests is also unlikely. Previous research by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) found that, if hardwood log supply from public native forests was reduced by 0.5–1.5% as a result of carbon offset projects (avoided harvest), the rate of leakage (proportion of emissions avoided through the projects that is displaced) into other native forests was likely to be 1.5–2.5% at the national level and 1–4% in NSW (ref. 23). The study also found an inverse relationship between the magnitude of the reduction in roundwood removals caused by the projects and the rate of leakage. Here, the cessation of harvesting in the SFR would result in a roughly 50% reduction in native hardwood roundwood removals from NSW public native forests, suggesting the rate of leakage in the conservation scenarios is likely to be at the lower end of the ABARES estimates[23,48].

On the basis of the ABARES results, and an analysis of the product mix from the region, in the global and national scenarios, we adopted the product substitution proportions shown in Supplementary Table 12. The product substitution proportions represent the proportion of foregone sawnwood products (including recycled products) replaced by the identified substitutes. Given the object of the study was to highlight the impact of policy institutions, we assumed these proportions remained stable throughout the projection period (in reality, they will fluctuate depending on market and institutional factors).

In the global scenarios, all domestic emissions associated with product substitution were excluded on the assumption that Australia adheres to its net emissions cap to 2020, and that it has emission constraints after 2020 that it abides by. In the NZ scenarios, where we assumed all imported substitute products were derived from New Zealand plantations, the sources and sinks were confined to international shipping emissions and forest and fossil fuel emissions associated with the production and distribution of Vietnamese woodchips. New Zealand forest and fossil fuel emissions associated with the production and distribution of the substitute sawnwood products were excluded because we assumed that, like Australia, New Zealand's net emissions are capped by a policy institution over the projection period.

Biomass in Vietnamese eucalypt plantations was modelled using equation (1) and FullCAM, with the parameters shown in Supplementary Table 13[51]. Fossil fuel emission estimates for Vietnamese woodchip production included emissions associated with the establishment and management of plantations, and the harvesting, haulage and processing of pulplogs[52,53].

For the Indonesia scenarios, we assumed all imported substitute products were derived from primary Indonesian rainforest, emissions and removals from which were modelled using equation (1) and FullCAM, with the parameters shown in Supplementary Table 13[54–56]. We assumed 60% of the logs derived from Indonesian forests were exported to Australia as substitutes for the sawnwood products foregone by the conservation of the SFR and that the remaining 40% were used to produce wood-based panels for domestic Indonesian consumption. The net forest and fossil fuel emissions for the Indonesian sawnwood products included those associated with the production and distribution of the wood-based panels on the basis that the withdrawal of SFR log supply triggers the increase in harvesting in Indonesia. The fossil fuel emissions included in the Indonesian scenario covered those associated with harvesting, haulage and processing of logs, and the transportation of products to market[52,53].

International shipping emissions were estimated on the assumption that woodchips are shipped in bulk cargo vessels (>52,000 deadweight tonnage (dwt)) with an initial mean emissions-intensity of 0.0058 kg CO_2e per tkm (refs 57,58). Sawnwood products were assumed to be transported in either container (3,000 to 8,000 twenty-foot equivalent units (TEU)) or general cargo (>10,000 dwt) vessels, with a weighted initial mean emissions-intensity of 0.0153 kg CO_2e per tkm (refs 57,58). In both instances, the emissions-intensity was assumed to decline linearly by 25% to 2050 and 95% by 2113 (refs 57,58).

In the sustainable use reference case, woodchips were assumed to be shipped between Australia (Eden) and Japan, with a weighted average one-way distance of 9,065 km. In the NZ scenario, the weighted average one-way international shipping distance between New Zealand and Australia was estimated to be 2,492 km. The weighted average one-way distance between Vietnam and Japan was 4,191 km. In the Indonesia scenarios, the weighted average one-way shipping distance for sawnwood products exported to Australia was 6,771 km. Distances were calculated using the SeaRates Port Distance calculator (http://www.searates.com/reference/portdistance).

In the national scenarios, domestic emissions and removals from the production of domestic substitutes were included in the analysis (Supplementary Tables 1 and 2). For substitution by domestic plantation (coniferous) sawnwood and wood-based panels, the assumed substituted sawnwood product mass was converted into a sawlog equivalent estimate (m^3) using the Australian Government's harvested wood product model[31,40]. The sawlog equivalent estimate was then used for the purposes of calculating the forest and fossil fuel-based life-cycle emissions associated with these products (see Supplementary Data File for energy factors, emission factors and transport assumptions). The on-site forest carbon fluxes from domestic plantations were modelled using the Tier 2 capabilities of FullCAM and the Australian Government's pre-1990 NSW and Victoria softwood plantation plots[31,32]. It was assumed for these purposes that, in the short-term (one rotation), the increase in demand for substitute softwood products (and associated increase in log prices) prompts forest managers to shorten the regeneration harvest age. At the same time, the rise in demand and prices also trigger an increase in softwood plantation establishment, which was assumed to occur on cleared grazing or cropping land. Meeting the extra demand for plantation softwood logs caused by the cessation of harvesting in the SFR was estimated to require shortening of the rotation length on 1,189 ha of existing softwood plantations and an expansion of 1,163 ha (refs 31,32).

For substitution by other domestic native wood products, we estimated the full life-cycle emissions associated with the substitute products (on-site forest carbon plus fossil fuel emissions) using a total log equivalent estimate (m^3) (sawlog, other log and pulplog). The leaked on-site forest carbon emissions were estimated to be 5.8% of the equivalent on-site savings through conservation; more than double the median leakage estimate from the ABARES study[23].

For substitution by domestic non-wood products, we applied a product displacement factor of 2.1 tC in the first year of the projection[4], declining thereafter by 1% per annum (to reflect the impact of policy institutions). In the national scenarios, the life-cycle emissions associated with imports were excluded.

Bioenergy and the displacement of fossil fuel-based electricity generation. Supplementary Table 14 contains details of the key specifications and parameters used to model domestic electricity generation from forest biomass. The specifications for the generators were based on a 5.5 MW biomass generator proposal put forward by the owners of the only woodchip mill in the region in 2009 (ref. 42). As the table shows, in the national scenarios, the efficiency of bioenergy generation was assumed to improve over time as a consequence of the incentives provided by policy institutions[59].

It is common in forest-related LCAs to assume bioenergy always displaces emissions-intensive generation[4–6,14,15]. We applied the same approach in the basic bioenergy scenarios, assuming forest bioenergy displaces subcritical pulverized black coal-fired electricity generation (the dominant type of electricity generation in New South Wales) throughout the projection period. The assumed emissions-intensity of displaced generation was based on a weighted average of coal generation in NSW in 2012–2013 (Supplementary Table 15)[60].

In the national bioenergy scenarios, because of the LRET, we assumed forest bioenergy displaces renewables (zero emissions) until 2030. After 2030, the bioenergy generation was assumed to displace subcritical pulverized black coal between 2031 and 2059, natural gas between 2060 and 2075, and an unspecified low-emission generator until the end of the projection period. These assumptions were based on modelling undertaken by the Australian Treasury for the purposes of Australia's former carbon pricing scheme[61]. In the first year of the projection period, the displaced coal generation was assumed to have the same emissions-intensity as shown in Supplementary Table 15. Thereafter, it was assumed to decline linearly to 0.96 kg CO_2e kWh in 2059. The emissions-intensity of natural gas generation in the first year of the projection period was based on a weighted average of gas (open and combined cycle) generation in NSW in 2012–2013 (Supplementary Table 16)[60]. It was conservatively assumed to decline linearly to 0.44 kg CO_2e kWh in 2075. The unspecified low-emission generator was assumed to have a static emissions-intensity of 0.05 kg CO_2e kWh (ref. 61).

References

26. Forests NSW *Performance Audit Report: Yield Forecasts – Southern Regional Forest Agreement, South Coast Sub-region* (NSW Government, 2011).
27. Forests NSW *Performance Audit Report: Yield Forecasts – Southern Regional Forest Agreement, Tumut Sub-region* (NSW Government, 2011).
28. Forests NSW *Performance Audit Report: Yield Forecasts – Eden Regional Forest Agreement* (NSW Government, 2011).
29. NSW Government *NSW Forest Agreements Implementation Report 2008–2009* (NSW Government, 2011).
30. NSW Government *NSW Forest Agreements Implementation Report 2009–2010* (NSW Government, 2011).
31. Australian Government *National Inventory Report 2012: The Australian Government Submission to the United Nations Framework Convention on Climate Change* (Commonwealth of Australia, 2014).

32. Richards, G. & Evans, D. Development of a carbon accounting model (FullCAM vers. 1.0) for the Australian continent. *Aust. For.* **67,** 277–283 (2004).
33. NSW Government *Integrated Forestry Operations Approval for the Southern Region* (NSW Government, 2013).
34. Ximenes, F., Gardner, W. D. & Marchant, J. *Total Biomass Measurement and Recovery of Biomass in Log Products in Spotted Gum* (*Corymbia maculata*) *Forests of SE NSW* (Commonwealth of Australia, 2005).
35. Rothe, A. *Forest Biomass for Energy: Current and Potential Use in Tasmania and a Comparison with European Experience* (University of Applied Sciences, Weihenstephan, 2013).
36. Farine, D. R. *et al.* An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia. *Glob. Change Biol.* **4,** 148–175 (2012).
37. Illic, J., Boland, D., McDonald, M., Downes, G. & Blackmore, P. *Wood Density Phase 1—State of Knowledge* (Commonwealth of Australia, 2000).
38. Bertalanffy, L. Quantitative laws in metabolism and growth. *Q. Rev. Biol.* **32,** 217–231 (1957).
39. Richards, F. J. A flexible growth function for empirical use. *J. Exp. Bot.* **10,** 290–300 (1959).
40. Richards, G. *et al.* Developing a carbon stocks and flows model for Australian wood products. *Aust. For.* **70,** 108–119 (2007).
41. Tucker, S. N. *et al. Life Cycle Inventory of Australian Forestry and Wood Products* (Forest Wood Products Australia, 2009).
42. *Greenhouse Gas Impact Assessment: 5.5 MW Biomass Power Plant—Report prepared for South East Fibre Exports* (URS, 2009).
43. Australian Government *Australian National Greenhouse Accounts: National Greenhouse Accounts Factors* (Commonwealth of Australia, 2013).
44. State Forests of NSW *Social, Environmental and Economic Reports* (Forestry Commission of NSW, 2000–2003).
45. Forests NSW *Social, Environmental and Economic Reports* (NSW Government, 2004–2007).
46. Forests NSW *Annual Reports* (NSW Government, 2008–2012).
47. Bureau of Rural Sciences *Australia's State of the Forests Report 2003* (Commonwealth of Australia, 2003).
48. *Annual Report 2012–13: Sustainability Supplement* (Forestry Corporation of NSW, 2013).
49. *FAOSTAT: ForesSTAT* (FAO, 2014).
50. *Timber Market Survey* (URS, 2014).
51. Sein, C. C. & Mitlöhner, R. *Eucalyptus Urophylla S. T. Blake: Ecology and Silviculture* (CIFOR, 2011).
52. *Emission Factors Compilation* (WRI, 2012).
53. Brander, M. *et al. Electricity-Specific Emission Factors for Electricity Generation* (Ecometrica, 2011).
54. Berry, N. J. *et al.* The high value of logged tropical forests: lessons from northern Borneo. *Biodivers. Conserv.* **19,** 985–997 (2010).
55. Ziegler, A. D. *et al.* Carbon outcomes of major land-cover transitions in SE Asia: Great uncertainties and REDD+ policy implications. *Glob. Change Biol.* **18,** 3087–3099 (2012).
56. Gibbs, H. *et al.* Monitoring and estimating tropical carbon forest stocks: Making REDD a reality. *Environ. Res. Lett.* **2,** 045023 (2007).
57. Buhaug, Ø. *et al. Second IMO GHG Study 2009* (International Maritime Organization, 2009).
58. Smith, T. *et al. Third IMO GHG Study 2014* (International Maritime Organization, 2014).
59. Koop, K., Koper, M., Bijsma, R., Wonink, S. & Ouwens, J. D. *Evaluation of Improvements in End-Conversion Efficiency for Bioenergy Production* (European Commission, 2010).
60. Clean Energy Regulator *Greenhouse and Energy Information 2012–2013* (Commonwealth of Australia, 2014).
61. Australian Government *Strong Growth, Low Pollution: Modelling a Carbon Price* (Commonwealth of Australia, 2011).