A natural capital accounting framework to communicate the environmental credentials of individual wool-producing businesses

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Abstract

Purpose – This paper aims to demonstrate methods that sustainability-conscious brands can use to include their primary producers in the measurement and reporting of the environment and sustainability performance of their supply chains. It explores three questions: How can farm businesses provide information required in sustainability reporting? What are the challenges and opportunities experienced in preparing and presenting the information? What future research and policy instruments might be needed to resolve these issues.

Design/methodology/approach – This study identifies and describes methods to provide the farm-level information needed for environmental performance and sustainability reporting frameworks. It demonstrates them by compiling natural capital accounts and environmental performance information for two wool producers in the grassy woodland biome of Eastern Australia; the contrasting history and management of these producers would be expected to result in different environmental performances.

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Findings – The authors demonstrated an approach to NC accounting that is suitable for including primary producers in environmental performance reporting of supply chains and that can communicate whether individual producers are sustaining, improving or degrading their NC. Measurements suitable for informing farm management and for the estimation of supply chain performance can simultaneously produce information useful for aggregation to regional and national assessments.

Practical implications – The methods used should assist sustainability-conscious supply chains to more accurately assess the environmental performance of their primary producers and to use these assessments in selective sourcing strategies to improve supply chain performance. Empirical measures of environmental performance and natural capital have the potential to enable evaluation of the effectiveness of sustainability accounting frameworks in inducing businesses to reduce their environmental impacts and improve the condition of the natural capital they depend on.

Social implications – Two significant social implications exist for the inclusion of primary producers in the sustainability and environmental performance reporting of supply chains. Firstly, it presently takes considerable time and expense for producers to prepare this information. Governments and members of the supply chain should acknowledge the value of this information to their organisations and consider sharing some of the cost of its preparation with primary producers. Secondly, the "additionality" requirement commonly present in existing frameworks may perversely exclude already high-performing producers from being recognised. The methods proposed in this paper provide a way to resolve this.

Originality/value – To the best of the authors' knowledge, this research is the first to describe detailed methods of collecting data for natural capital accounting and environmental performance reporting for individual farms and the first to compile the information and present it in a manner coherent with the Kering EP&L and the UN SEEA EA. The authors believe that this will make a significant contribution to the development of fair and standardised ways of measuring individual farm performance and the performance of food, beverage and apparel supply chains.

Keywords Natural capital accounting, SEEA, EP&L, Sustainability, Wool, Regenerative agriculture, Carbon sequestration, GHG

Paper type Research paper

1. Introduction

Greenhouse gas (GHG) emissions, land degradation and biodiversity loss threaten food security and attainment of sustainable development goals (SDG; FAO and GEF, 2018; IPBES, 2018; Willett *et al.*, 2019).

To achieve change, financial organisations are increasingly allocating capital to entities that are addressing these issues (Generation, 2012; Guthrie, 2016; IFAC, 2015), creating both opportunities and accountability challenges for managers of natural capital (NC). Investors and brand leaders around the world are increasingly integrating environmental, social and corporate governance factors into their strategic and operational decisions (Van der Lugt *et al.*, 2020) by investing in the development and application of frameworks and standards to measure, communicate and improve their environmental performance, inclusive of their supply chains (Capitals Coalition, 2020a, 2020c; Kashmanian and Moore, 2014; Kering, 2018; Natural Capital Coalition, 2016a; Patagonia, 2014; Van der Lugt *et al.*, 2020). Governments are also reliant on corporate reporting as a primary source of information about SDG progress (UNCTAD, 2016).

However, there is a lack of consistency in the reporting scope and methods, with organisations using a wide range of different approaches (Accountancy Europe, 2019; Bartels *et al.*, 2016; EY and BCCCC, 2017; FSC and ACSI, 2015; Kwon *et al.*, 2018; Loweth, 2017; Van der Lugt *et al.*, 2020). The 2020 Carrots and Sticks report on global trends in sustainability reporting highlighted the existence of over 600 reporting provisions (an increase from 383 in 2016) (Van der Lugt *et al.*, 2020).

Whether there should be a single agreed standard for sustainability reporting is an active area of debate. While it is recognised that the diversity of reporting frameworks and instruments may reduce their utility for comparing the performance of different businesses (Blackrock, 2016; CDSB, 2018b; EY and BCCCC, 2017; Kwon *et al.*, 2018; Lambooy *et al.*, 2018), it is also accepted that a "one-size-fits-all" approach may not be appropriate (UNCTAD, 2016; Van der Lugt *et al.*, 2020).

Despite the diversity of approaches, there is some level of agreement about the issues that should be reported. The key disclosure themes and indicators of environmental performance covered or recommended in sustainability reporting frameworks include GHG emissions, energy use, water consumption (use), water and air pollution, waste generation, and impacts on biodiversity and ecosystem services (ES) due to land use changes (UNCTAD, 2016; Van der Lugt *et al.*, 2020). However, the lack of consistency in the inclusion of primary producers may create challenges for comparison of the environmental performance of businesses and supply chains, especially those in the food, beverage and apparel sector.

Primary production (largely comprised a collection of small individual farm businesses) is estimated to represent more than one-quarter of the environmental impacts in food, beverage and apparel supply chains (Kering, 2018; Capital Coalition, 2016b, 2016c). However, to the authors' knowledge, methods and standards for quantifying these indicators for input to sustainability reporting frameworks have not been described in sufficient detail for them to be widely adopted by accountants servicing individual farm businesses. Without the capacity to include and aggregate the individual performance of primary producers into indicators required for sustainability reporting, information about the environmental performance of food, beverage and apparel supply chains is incomplete and potentially misleading, and the use of sustainability reporting as a performance improvement strategy is constrained.

This study makes a practical contribution to addressing this important shortcoming by identifying approaches to compiling the farm-level information needed for environmental performance and sustainability reporting frameworks. Recent advances in NC accounting hold much promise for supporting sustainability reporting via the collection and collation of information using consistent and repeatable approaches and the linking of environmental performance with financial performance (Barker, 2019). Using a case study approach, this study focuses on the utility of NC accounting and its application to environmental profit and loss reporting by Kering (www.kering.com), a global luxury group with an explicit focus on contributing positively to the SDG.

Kering is a significant purchaser of agricultural products and considers the environmental (and animal welfare) performance of individual primary producers when selecting wool and other goods for the apparel it sells (Kering and Savory Institute, 2018). Working with PwC, a leading accountancy and consulting firm, it has developed an Environmental Profit and Loss statement (EP&L) (PwC, 2015) to summarise the environmental impacts and dependencies across its supply chain. The approach was first trialled by PUMA in 2011, and Kering has continued to develop and improve the approach (Kering, 2013, 2018).

Kering's EP&L uses estimates of physical environmental indicators to quantify and value, in monetary terms, societal impacts related to changes in the environment due to activities across its corporate value chains (PwC, 2015). The EP&L is designed to help decision-makers understand the impacts of their operations and supply chains, and to identify opportunities to improve performance (Brooke *et al.*, 2016; Kering, 2013, 2020a, 2020b); it covers the indicators commonly included in environmental performance and sustainability reporting frameworks (UNCTAD, 2016); Van der Lugt *et al.*, 2020).

However, just as a financial profit and loss statement communicates inflows and outflows of financial capital associated with changes to assets and liabilities under an enterprise's management and does not communicate the value of the underlying assets and liabilities at a point in time, the EP&L communicates loss or change of ES associated with changes to land use as a proxy for NC; it does not quantify the condition or value of NC stocks at a point in time (Brooke *et al.*, 2016). As a result, it is very difficult to interpret (using an EP&L) the impacts of the organisation on the NC that the organisation (and society more broadly) is dependent on, or the capacity of that underlying NC to continue to produce the corresponding environmental goods and services.

In its initial inception, the EP&L framework included the concept of *land use* and used biomass loss as a proxy to estimate ES and biodiversity loss. This initial approach assumed almost total loss of ES and biodiversity from the conversion of natural landscapes to pasture and croplands for agriculture (PwC, 2015); this overestimated the impact of primary production on ES and biodiversity.

Recognising this and that the approach did not adequately reflect modern methods of agricultural management of NC, Kering introduced EP&L factors associated with different modes of agricultural practice (Kering, 2018). Under this system, producers are rated according to whether they use conventional, organic, restorative or regenerative practices, based on the assumption that different modes result in different impacts on ES and, therefore, on the EP&L (Kering, 2018).

While it is well-accepted that farm management practices can have significantly different impacts on NC and ES production, the nomination of practice type is an unreliable indicator of activities and outcomes (Dessart *et al.*, 2019; Pannell and Claassen, 2020) and may not provide a faithful, neutral and error-free view of the environmental impact of an individual farm; this is an important principle in accounting practice (IASB, 2018). Thus, more direct empirical measures are required to build confidence in the integration of environmental impacts across the supply chain.

To do so requires information about the type and condition of NC, as its type and condition governs the type, range, quality and quantity of ES; this knowledge is important in the selection of appropriate practices to use and manage NC (Capitals Coalition, 2020a; UNSD, 2017). This gap can be addressed by NC accounting (NCA; Forico, 2020; Marais *et al.*, 2019; Ogilvy, 2015, 2020; Ogilvy and Vail, 2018; Stewart *et al.*, 2020).

NCA or environmental and economic accounting (e.g. SEEA EA) provides guidance for the empirical measurement and accounting for NC, and the ES that NC generates (UNCEEA, 2021a), including estimates of changes to NC and ES resulting from land use change. Formal frameworks for compiling, aggregating and analysing information about NC provide standardised approaches for investment analysts (Accountancy Europe, 2019; Blackrock, 2016; Capitals Coalition, 2020b; Hoogervorst, 2019; Van der Lugt *et al.*, 2020) to judge whether changes to NC, resource use and environmental performance indicate whether the entity or supply chain is maintaining, consuming or regenerating its stocks of natural, financial, produced and social capital. Application of the SEEA at the individual entity level can also provide useful information for policy design and evaluation (EC *et al.*, 2012); however, the methods to do so require further development (Hein *et al.*, 2020).

Together, EP&L and NCA cover the environmental performance issues (i.e. GHG emissions, energy use, water use, waste, pollution, changes to NC), land use changes, and biodiversity losses commonly contained within other environmental and sustainability reporting frameworks (Kwon *et al.*, 2018; UNCTAD, 2016; Van der Lugt *et al.*, 2020). Thus, the learnings from this study could inform the future development of other frameworks, such as the Global Reporting Initiative (GRI), Integrated Reporting Framework (IR), Climate Disclosure Standards Board (CDSB) and Principles for Responsible Investment (PRI) (CDSB, 2018a; GRI, 2016; IIRC, 2013; PRI, 2019), and future research about the impact of different frameworks on the environmental accountability of supply chains.

The core research questions explored in this paper are:

RQ1. How can farm businesses quantify their environmental performance on the environmental performance indicators included in the Kering EP&L and provide information about their NC that is coherent with the SEEA EA?

RQ2. What are the *challenges* and *opportunities* experienced in preparing and presenting the information?

RQ3. What *future research and policy instruments* might be needed to resolve these issues to achieve wide adoption of NC accounting in agriculture and empirical measurement of agricultural environmental performance?

To explore these questions, this paper focuses on wool production. Wool is an important Australian export commodity. The Australian wool (and sheep meat) industry has a strong focus on environmental sustainability (www.wool.com), and wool is a significant supply chain component of the global apparel (and food) sector, of which Kering is a major consumer.

We identified the biophysical measures required as inputs to an EP&L framework. We reviewed methods for producing this information from published and industry literature, and compiled this information in a manner consistent with the recommendations for ecosystem accounting in the SEEA EA. We demonstrated how a primary producer might present the information by compiling NC accounts for two farms that have contrasting land management histories and current farming practices and would, therefore, be expected to exhibit some differences (and similarities) in environmental performance. We reflected on the interpretation of the environmental performance information and the data collection and compilation experience. Finally, we shared insights and recommendations for further development of concepts and standards for measurement and accounting that are necessary for the broad adoption of NC and environmental performance at the farm level.

2. Methods

2.1 Demonstration farm selection

Two comparable farms were selected for this study to demonstrate the preparation of farm-level information for use in EP&L and SEEA EA accounts. The farms are situated close to each other in the agriculturally important sheep-wheat zone of Australia; this region is also home to a recognised endangered ecological community referred to as box-gum woodland. This community occurs on moderate to highly fertile soils with rainfall ranging between 400 and 1200 mm (TSSC, 2010); it extends on a sub-coastal band to the west of the Great Dividing Range from Southern Queensland, through New South Wales (NSW) to Southern Victoria, with separated representation in regions of Tasmania. Some agricultural practices such as clearing, fertiliser use and inappropriate grazing regimes are negatively associated with the health of the box-gum woodland and its capacity to persist and deliver ES such as carbon sequestration and storage, forage production and protection of soil and water quality (Dorrough *et al.*, 2011; McIntyre, 2008; McIntyre and Lavorel, 2007; McIntyre *et al.*, 2002; Prober *et al.*, 2002; TSSC, 2010). The farms were selected based on their close location, and thus, shared climate and geographical characteristics, meaning that differences in NC and environmental performance are likely to reflect differences in historical and present management.

Farm 1 is a wool and beef-producing property that, following historical clearing, fertiliser application and over-sowing with leguminous species has, since the mid-1980’s, been managed in ways that minimise threats to the grassy woodland vegetation. This includes the discontinuation of cultivation and fertiliser application, implementation of intensive fencing infrastructure and planned grazing practices (short graze periods, long and planned rests for pasture recovery). Pastures are monitored regularly with stock not returned until key perennial pasture species are considered (according to the farmer's judgement) to have recovered sufficiently such that the pasture can be re-grazed without compromising future plant vitality and survival. The cessation of fertiliser use and altered grazing strategy have resulted in natural regeneration of trees indigenous to the area and recovery of the diversity of the ground layer. This is consistent with published mechanisms (Curtis and Wright, 1993; Fischer *et al.*, 2009; McIntyre *et al.*, 2002; Vesk and Dorrough, 2006).

Farm 2 is a wool and timber-producing property that has been historically cleared, with grasslands either fertilised and/or replaced consistent with conventional practices for the region. In recent decades, the landholders have invested substantially in managed forestry and environmental plantings to build biodiversity and NC to support the production of wool and timber. The landholder aims to increase tree cover to 35% of the farm in the form of managed forests and habitat or shelter.

2.2 Physical estimates for EP&L input

Methods for estimating the annual contributions of primary producers to EP&L (in physical terms) are described in the following order:

- GHG emissions;
- water use (consumption);
- water pollution;
- air pollution;
- waste; and
- land use.

This is followed by descriptions of methods, coherent with the UN SEEA EA, to characterise selected aspects of the NC of each farm and to present these in NC accounts. Characterisation of NC enables estimation of ecological health and biodiversity, and ES such as carbon sequestration, and soil and waterways protection. This, in turn, can be used to faithfully represent (IFRS, 2018) a farm's environmental performance, estimate (or explain) changes to ES production that might occur over time, and determine the environmental profit or loss (Brooke *et al.*, 2016).

To reflect interannual variation in seasonal and market conditions, and represent the characteristic performance of the operation, this study used a multi-year average of annual data collected from each farm's financial and operational records.

Both farms in this study carried cattle (*Bos taurus*) and sheep (*Ovis aries*). To generate EP&L metrics per unit of production of wool (Kering, 2013) (consistent with the per net value-added concepts proposed by the United Nations Environment Programme; UNCTAD, 2016), resource use was allocated to the sheep and cattle enterprises on a dry sheep equivalent (DSE) basis [1], and the ratio of sheep DSE to cattle DSE was used in the initial apportionment. Sheep enterprise resource use was apportioned between wool and meat production using the biophysical allocation factor of 41.7% for wool products (Wiedemann *et al.*, 2016).

2.2.1 Green gas house emissions. Estimations of GHG emissions associated with raw material production should include emissions associated with the production and transport of farm inputs (e.g. fertiliser) and purchased livestock (Scope 3 emissions), as well as emissions from direct on-farm operations (Scope 1) and purchased electricity (Scope 2)

(Kering, 2013, 2018; Capital Coalition, 2016b, 2016c; WBCSD and WRI, 2004). Accordingly, the scope of GHG estimation should include:

(1) Scope 1 emissions (on-farm):
   - CO_2: fossil fuel use, lime, urea application
   - CH_4: fossil fuel use, enteric, manure
   - N_2O: fossil fuel use, urine and dung, atmospheric deposition (animal manure and fertiliser), leaching and run-off (animal manure and fertiliser)

(2) Scope 2 emissions (on-farm):
   - Emissions from purchased electricity

(3) Scope 3 emissions (pre-farm):
   - Production and transport of fossil fuels
   - Production and transport of purchased inputs (fertiliser, fodder, grain, livestock)

Scope 1: animal and other agriculture GHG emissions were calculated according to the methods described in the National Inventory Report 2018 – Volume 1 (DISER, 2020b). Data were collected from farm records and interviews, and the S-GAF and B-GAF calculators were used (Doran-Browne and Eckard, 2018; Eckard, 2020). The results were adapted to reflect the global warming potentials and emissions factors used in the National Inventory Report 2018 (DISER, 2020b). Liveweight, liveweight gain, crude protein and dry matter digestibility parameters were based on state-based values defined in the summary tables in Appendices 5.B and 5.D. Expenditure on fossil fuel was converted to physical volume based on locality and time-based conversion factors published by industry (Fleet Auto News, 2018).

Key parameters, emissions factors and uncertainty associated with the estimation methods for Scope 1 emissions are outlined in Table B1.

Scope 2: Emissions from electricity generation were calculated using the emissions factors described in the National Greenhouse Accounts Factors – October 2020 (DISER, 2020a).

Scope 3: Pre-farm Scope 3 emissions associated with livestock purchases were estimated using the following emissions factors: 11.7 kg CO_2e/kg liveweight for cattle (Wiedemann *et al.*, 2016); 9.3 kg CO_2e/kg liveweight for sheep (Wiedemann *et al.*, 2016). Pre-farm emissions associated with purchased fertiliser and amendments were estimated using

Code for state	Summary description of state
S1A	Dense Grassy woodland/forest >50% canopy cover with a very diverse native ground-layer
S1B	Derived native grassland with a very diverse native ground-layer
S2A	Open grassy woodland with a very diverse native ground-layer
S2B	Derived native grassland with a diverse native ground-layer (but less diverse than State 1 A)
S3A	Remnant grassy woodland with some mature trees present and a moderately diverse and, mainly native, ground-layer
S3B	A moderately diverse and mainly native grassland with a few mature remnant trees remaining
S4	Grassland with a mix of native and exotic species and occasional scattered remnant trees
S5	Species poor and predominantly exotic grasses and < 3 native species. Remnant trees absent

Notes: These states are used to describe ecosystem assets on Australian farms located in the grassy woodland biome of Australia. Further details are provided in the Supplementary Materials (Table A1)

Table 1. Summary description of states within the grassy woodland biome

the following emissions factors: 0.97 kg CO_2e/kg synthetic fertiliser (Christie *et al.*, 2011); 0.23 kg CO_2e/kg superphosphate (Christie *et al.*, 2011); 0.89 kg CO_2e/kg urea (Christie *et al.*, 2011). Pre-farm emissions associated with feed purchase were estimated using the following emissions factors: 0.30, 0.25 and 0.20 kg CO_2e/kg feed for grain, hay/silage and lucerne, respectively (Christie *et al.*, 2011). Scope 3 emissions from electricity use were calculated using the emissions factors described in the National Greenhouse Accounts Factors – October 2020 (DISER, 2020a).

The EP&L does not, at present, require that GHG emissions are "net" of emissions and sequestration. As agriculture has the potential to sequester and store carbon, we complemented the emissions estimates with estimates for carbon storage and sequestration (Section 2.5).

2.2.2 Water consumption. Water consumption for livestock use was calculated based on livestock numbers derived from farm records together with localised climate factors (Luke, 1987) based on annual mean temperatures for each locality from the Australian Bureau of Meteorology. Water loss due to evaporation was included based on a dam efficiency factor of 0.175 (Wiedemann *et al.*, 2016). A water-stress index (WS) was derived for each farm (Pfister *et al.*, 2009) and was applied to the water consumption calculation. Normalised stress-weighted water use was derived using the worldwide WSI of 0.602 (Ridoutt and Pfister, 2013).

2.2.3 Water pollution. Water pollution as a result of nitrogen leaching and run-off from animal manure and applied fertiliser (biological or chemical) was calculated using the methods outlined in the National Inventory Report 2018 – Volume 1 (DISER, 2020b), with the S-GAF and B-GAF calculators (Doran-Browne and Eckard, 2018; Eckard, 2020).

2.2.4 Air pollution. In the Kering EP&L, air pollution from the farm relates to the generation of particulate matter (PM), mono-nitrogen oxides (NO_x) and sulphur dioxide (SO_2) (PwC, 2015). The burning of fossil fuels by farm vehicles and equipment is a source of all three pollutants, with PM also being generated as dust from agricultural activities. Emissions of carbon dioxide (CO_2) and methane (CH_4) were accounted for in the GHG emissions estimate.

Air pollution from vehicle emissions is governed by fuel quality standards, vehicle type and age (Fiebig *et al.*, 2014). We were unable to identify published methodology to support the estimation of air pollution associated with farm vehicles using local fuel supplies, and an empirical study was beyond the scope of this project.

Air pollution associated with dust generation from individual farms is difficult to directly quantify. As an alternative, this study applied the approach described in the SEEA EA to estimate the capacity of the land to avoid dust generation (UNSD, 2020b). Soil is judged to be vulnerable to wind erosion when the soil has less than 50% ground cover (Alt *et al.*, 2009). Bare ground proportions were quantified by the seasonal ground cover imagery statistics provided by FarmMap4D (FarmMap4D, 2017), and confirmed with field observations and estimations of the proportion of cultivated land each year based on the farm interviews. This was corroborated with satellite imagery (FarmMap4D and Google Earth^{TM}).

2.2.5 Waste. Waste generated from farming operations was estimated to result from wrapping of fodder and chemicals packaging; farm interviews and financial statements were analysed to estimate the types and amounts. This information was combined with information from suppliers to estimate the amount of packaging, and therefore, waste. For example, based on supplier websites, waste from fodder was estimated to be 1 kg of plastic waste per large bale.

2.2.6 Land-use/biodiversity. The method described by PwC for the valuation of environmental loss due to land use change involves estimation of the societal cost associated with the loss of a range of ES (PwC, 2015). A calculation was performed for each ES based on the following formula:

$$TLESV(\$)_{el} = A(ha)_{ml} * EESL(\%)_{el} * ESV(\$/ha)_{el}$$

where:

$TLESV(\$)_{el}$ = Total lost ES value for ES (*el*)
$A(ha)_{ml}$ = Attributable area (ha) for the production of a given material (*ml*)
$EESL(\%)_{el}$ = Extent of ES loss for ES (*el*)
$ESV(\$/ha)_{el}$ = ES value for ES (*el*)

The global societal cost of ecosystem loss due to the production of a material is then calculated by summing the total lost ES value for all ES.

Extent of ES loss: The original EP&L conception used proxies of relative biomass and species richness loss to calculate the extent of ES loss where site-specific information was not available (PwC, 2015). While this study gathered site-specific information about the type and condition of NC (ecosystem assets; EAs), undertaking an empirical assessment of each ES and biodiversity loss per property using fine-scale methods for operationalising environmental accounting (Jones, 2003; Jones and Solomon, 2013) and extinction accounting (Atkins and Maroun, 2018, 2020) was beyond the study scope. Instead, this study followed Lavorel *et al.* (2015), conceptualising the extent of ES change due to the land being used for agriculture as proportional to the change in ES relative to those produced by the original biome of the property. For the case study region, grassy woodland was the reference biome (i.e. State 1 A; Whitten *et al.*, 2010). Thus, the degree of change in the characteristics of the original biome relative to the present configuration of NC was estimated using ecosystem accounting methods drawn from the SEEA EA. The methods are described under the following sub-headings:

- spatial data and accounting for NC;
- accounting for ecosystem type and condition; and
- estimating carbon storage and sequestration.

Attributable area: this was calculated as the total extent of the property assigned to grazing multiplied by the ratio of sheep DSE to total DSE of the grazing enterprise, multiplied by the biophysical allocation factor of 41.7% for wool products (Wiedemann *et al.*, 2016).

2.3 Spatial data and accounting for NC (EA) extent

The NCA proposed in this study follows the SEEA EA in describing NC owned and controlled by an individual entity (i.e. business, family, government) as ecological assets described in physical terms based on the type, extent and condition of the ecosystem (Ogilvy, 2015, 2020; UNSD, 2017, 2020c). Following the principles of the SEEA EA, and as NCA is applied to individual entities, the ecosystem accounting area (EAA) is the land area owned/and controlled by the entity, including property ownership and property lease for business use (Ogilvy, 2020).

EAs are contiguous spaces of a specific type of ecosystem (ecosystem type; ET) in a similar condition. Additionally, in this study, the EAA was further divided into unique management areas, such as paddocks, yards, sheds, domestic and riparian areas, to reflect that management is usually conducted at this scale. The union between these management areas and the EA creates unique ecosystem units (EUs). The basic spatial unit (BSU) for NCA is metres (m), with accounting summaries presented in hectares (ha). This approach enables individual farm accounts to be aggregated to provide information about a region or catchment.

EAAs were defined using property details sourced from local government records to create farm boundary polygons using a commercial GIS tool, FarmMap4D (FarmMap4D, 2017). Paddocks, roads and infrastructure within the property were mapped using FarmMap4D. ETs were identified using state vegetation maps for NSW (Keith and Simpson, 2017) and satellite imagery to create a polygon-based ET layer using Google Earth^{TM}. The resulting two layers were combined (union) using EnSym (DELWP, 2018) to generate a detailed ecological asset register (EAR) containing a list of each unique EU.

2.4 Accounting for ecosystem type and condition

Following the SEEA EA, the NC accounts were compiled using ETs drawn from the IUCN Global Ecosystem Typology v1.01 (Keith *et al.*, 2020) with the biome of demonstration farms being T4 Temperate Woodlands. To accommodate agroforestry and silvopastoral systems sometimes used in Australia, this study developed a typology to describe the types of agroforestry observed on Farm 2 (Table 2).

Ecosystem condition is defined in the SEEA EA as the quality of an ecosystem in terms of its abiotic and biotic characteristics (UNSD, 2020a). Ecosystems with different attributes generate different ES and exhibit differences in biodiversity. To indicate the potential for a grassy woodland EU to provide a range of ecosystem goods and services, state and transition models (STM) established by ecological research relevant to the grassy woodland biome (Lavorel *et al.*, 2015; Spooner and Allcock, 2006; Whitten *et al.*, 2010) were applied to EUs in relatively natural condition, for both demonstration farms. The simplified STM for box gum grassy woodland (Whitten *et al.*, 2010) was used, which provides a scientifically coherent and holistic measure of the condition of this type of ecosystem. This model was further extended to include densely forested areas in a single STM. The application of a particular state (or transition) enabled an identity to be applied to each EU, providing

Level of replacement	Term used	Description
Fully replaced	Fully replaced, native, dense	Original vegetation mostly removed, planted trees of native origin, planted in a dense configuration
	Fully replaced, native, open	Original vegetation mostly removed, planted trees of native origin, planted in a sparse or open configuration
	Fully replaced, exotic, dense	Original vegetation mostly removed, planted trees of introduced/exotic origin, planted in a dense configuration
	Fully replaced, exotic, open	Original vegetation mostly removed, planted trees of introduced/exotic origin, planted in a sparse or open configuration
Partially replaced (augmented plantings into native vegetation - ground-layer and/ or mid and overstory)	Partially replaced, native, dense	Partially replaced native vegetation with dense plantings of native origin
	Partially replaced, native, open	Partially replaced native vegetation with sparse or open plantings of native origin
	Partially replaced, exotic, dense	Partially replaced native vegetation with dense plantings of introduced/exotic origin
	Partially replaced, exotic, open	Partially replaced native vegetation with sparse or open plantings of introduced/exotic origin

Notes: States were either fully replaced states (overstorey and ground layer modified substantially through clearing and/or replacement and nutrient enrichment) or partially replaced (augmented plantings into ground layer and/or mid/overstorey native vegetation

Table 2. Summary descriptions of additional states used to describe ecosystem assets where native or exotic tree planting occurred

quantitative metrics relating to the characteristics of the ecosystems and their use as suggested by the SEEA EA (UNSD, 2020a; Table 5.2).

For more natural systems (less modified systems), estimates of the overall extent (spatial coverage) of each state (or transition) were compiled for the demonstration farm, according to the STM. Individual states have particular characteristics, such as an approximate number of native species, quantity of standing and fallen dead timber, tree canopy cover, age distribution of live trees, and approximate levels of phosphorous (P) and nitrogen (N) (Whitten *et al.*, 2010). These characteristics give an indication of ES that are likely within a particular state. The different vegetation attributes for each state of a grassy woodland (the biome where this study was situated) are summarised in Table 1. Further details, including the fertiliser application for each state, are provided in the Supplementary Material (Table A1).

To describe the EUs of more modified, less-natural systems created by planting native and exotic trees and shrubs for agroforestry and environmental purposes, the grassy woodland STM model was extended with categories reflecting anthropogenic ES observed on the second farm. These additional states are shown in Table 2. This approach follows the IUCN approach to describing intensive anthropogenic terrestrial ES (Keith *et al.*, 2020). See Table A1 for further details of the STM used for these modified ETs.

To reflect the use of NC for livestock production, EAs were also classified with respect to their capacity to produce good-quality forage for livestock. A land condition classification system for grazing (Very Good, Good, Fair, Poor, Very Poor; Table 3) was drawn from industry good-practice for grazing management on naturalised pastures (MLA, 2016; Queensland Government, 2017; Ryan *et al.*, 2013; Walsh and Cowley, 2014). Principles from these were adapted to naturalised grasslands in temperate regions for this study. This

Category	Description
Very Good (A)	Very good land condition that has high levels of groundcover (>90%), including perennial tussock species and litter that contribute to soil protection and water and nutrient retention, and an appropriate mix of perennial, palatable and persistent species. Few weeds are present and soil erosion is absent. A good amount of biomass is retained (>1500 kg ha^{-1}), even where animals are present or after a grazing event
Good (B)	Similar to A with good land condition that has high levels of groundcover (70–90% coverage). There is some decline in perennial, palatable and persistent species and larger tussocky species (including litter) that contribute to soil protection (and water and nutrient retention) compared to class A and likely to be a minor presence of weeds. There may be signs of previous erosion and potential for current erosion in some areas. Reasonable biomass (a golf ball would not be seen from a few m away) is retained even where grazing animals are present
Fair (C)	There are reasonable levels of groundcover (up to 70%), a low diversity of palatable and perennial species and persistent native species that protect soil assets in poor times are missing. Annual or invasive perennial weeds are significant. A high proportion of bare ground is likely to be present (>50%) in some years and obvious signs of erosion with current susceptibility to erosion high. Low biomass (a golf ball easily seen from a few metres away)
Poor (D)	Low levels of groundcover (<50%) with a fair proportion of bare ground (>30%), low pasture biomass most of the time and (likely to very low in extended dry times), a low diversity of perennials and dominated by unpalatable species and annual weeds
Very Poor (E)	Few (if any) perennial species are present and it is a severe and hostile environment for plant growth (i.e. scalding, salinity, severe and continuing gullying in susceptible areas). Potential and likelihood of weed invasion is high

Table 3. Categories of pasture condition for ecosystem accounting

approach incorporated measures used in the Ecological Outcomes Verification (EOV; Savory Institute, 2019) to verify that farms are regenerating NC associated with agricultural production (Kering and Savory Institute, 2018). The NC accounts proposed complement EOV by providing a way to organise detailed grazing condition data under the normative scale recommended by the SEEA EA (Keith *et al.*, 2019; UNSD, 2020a).

Important aspects of NC stewardship in agriculture include the protection of waterways from agricultural impact and the encouragement of biodiversity (Bennett *et al.*, 2014; Cole *et al.*, 2020). The NCA in this study used the functional characteristics described in the grassy woodlands STM to characterise whether riparian zone EUs were of a type and condition to provide ES that both improved water quality and protected biodiversity associated with riparian areas.

The provisional ETs and extents established using remotely-sensed data were validated through field observations at pre-selected representative locations on the property and through interviews with the farmer regarding management history, including prior application of fertiliser, cultivation and clearing history (Ogilvy *et al.*, 2018). Due to their expense, field observations were necessarily limited to a few representative points, with these points selected using indicators of disturbance patterns derived from the seasonal ground cover statistics generated by FarmMap4D [2] and Google Earth™ imagery. A site was considered representative of an ET if it demonstrated a similar disturbance pattern to other areas of the same ET. The STM, and grazing land condition for areas not directly observed by the ecologist were imputed based on seasonal ground cover statistics from FarmMap4D, professional judgement and information from interviews with the producers. The EAR denotes which EUs were assessed by observation and which were imputed.

2.5 Estimating carbon storage and sequestration

Carbon stock accounts are a desirable component of SEEA EA (Ajani *et al.*, 2013; Keith *et al.*, 2021; Lof *et al.*, 2017; UNSD, 2017), and carbon sequestration is a valuable ES that can be provided by agriculture. Accordingly, ex-post [3] estimates of carbon sequestration and carbon stocks should be included in NCA. Bio-carbon and soil carbon stocks in the NC of a farm enterprise can be estimated using:

- Direct measurements of biomass to provide accurate estimates of bio-carbon and soil carbon stocks, and of changes to stocks resulting in changes to EA condition, including from transitions between states (Berry *et al.*, 2010; Jonson and Freudenberger, 2011; Keith *et al.*, 2000).
- Published estimates of bio-carbon and soil carbon stocks associated with different ecological communities (Cardinael *et al.*, 2018).
- Estimates of carbon stocks and sequestration rates based on models such as the Full Carbon Accounting Model (FullCAM) tool [4] used in Australia for each of the major ETs of the farm.

Due to the reliance on empirical inputs for biomass, management and disturbance regimes, the cost and technical complexity of Approach 1 was beyond the scope of this study. It would also likely be regarded as cost-prohibitive unless the farm business was participating in research on model calibration or remote sensing technology, or could offset the costs with revenue from participation in a formal carbon offset project.

In contrast, whilst Approach 2 is a cost-effective approach to estimating carbon stocks and sequestration rates, it has limited accuracy due to the present paucity of published location-specific estimates of bio-carbon stocks and sequestration rates. Using a single lookup table for a range of locales does not allow for variation across soil types and climatic zones.

For the experimental NCA approach in this study, Approach 3 using FullCAM was used to develop a site-specific set of carbon sequestration models for each type of ES on each farm. The resulting model was then used to determine carbon stocks and sequestration rates for each state or transition relevant to that ET. Existing Emissions Reduction Fund (ERF) (CER, 2020) methodologies and parameters for FullCAM were not used because they do not allow for mixed forest-agricultural systems, do not accommodate natural grassy woodlands, sparse plantings or regeneration of trees in grazed landscapes, and do not allow for the ongoing sequestration of existing trees in addition to modelling sequestration related to regrowth (CER, 2020). Furthermore, the existing ERF methodologies require each EU to be modelled separately, which is onerous when the objective is to estimate sequestration for a whole farm.

To overcome this, models were created for each of the following scenarios to represent the EAs of the demonstration farms:

- Grassy woodlands and forests – FullCAM parameters were configured to reflect the clearing history (determined in farm interviews), present condition (position in the STM) and any expected regeneration or degradation of grassy woodland ecosystems as recorded in the ecosystem accounts. These were then assigned a carbon stock and annual sequestration rate for each of the states and transitions from the STM.
- Fully-replaced exotic plantations – to reflect these types of agroforestry assets, FullCAM parameters incorporated the species composition observed in the ecosystem accounts and their management (determined from farmer interviews), including thinning and harvest regimes.
- Fully-replaced native plantations – to reflect dense block native environmental plantings, FullCAM parameters incorporated the species composition observed in the ecosystem accounts and their management (determined from farmer interviews).
- Fully-replaced native shelterbelts – FullCAM parameters modelled the native environmental plantings in shelterbelt configuration.

To reflect the differences in the annual sequestration rates of different states in the STM, rates for the grassy woodlands model were calculated as a 20-year average (±10 years from the mid-point of the state or transition) based on the placement of the state or transition on the modelled growth curves. For replaced plantations and shelterbelts, the carbon stock levels and sequestration rates were calculated as the average of three age bands: young (0–20 years), intermediate (20–40 years) and mature (40–60 years). See Supplementary Materials (Table C1 and C2) for details of the settings used for the FullCAM models.

The resulting sequestration rates were used as look-up tables and applied to each EU in the EAR based on the ecosystem type and state, with additional controls to allow for the density of partially-replaced states (the percentage of cover of the plantations calculated using the iTree canopy tool (https://canopy.itreetools.org/) based on 100 samples) and the determination of whether an individual EU was regenerating (assigned the sequestration rate of that state or transition), static (sequestration rate of zero) or declining (assigned a negative sequestration rate based on the state or transition category of the EU).

2.5.1 Exclusions in calculating the carbon sequestration rates. The assessment of reforestation and regeneration of native vegetation in this study excluded estimates of the contribution of soil to the sequestration rate of carbon in the EAs. This is because there is considerable uncertainty and variability in the published soil carbon sequestration ranges following re-forestation (Paul *et al.*, 2002; Sanderman and Baldock, 2010; Specht and West, 2003). This is consistent with the methodology of the Carbon Farming Initiative (DAWR, 2017).

Similarly, the grassland vegetation (the "crop") sequestration rate was also assumed to provide zero contribution to the ES sequestration rate. Carbon stocks associated with grassland can be highly variable over time (due to climatic inputs), and the amount of carbon stored in pasture biomass is insignificant compared to the biomass/carbon stored in trees and debris. Its exclusion does not materially change the outcomes and simplifies the process of deriving a sequestration rate estimate.

Static values for soil and pasture carbon stocks were based on a median value derived from studies of carbon stocks (MacDonald *et al.*, 2015; Orgill *et al.*, 2014; Orgill *et al.*, 2016; Wheeler *et al.*, 2016; Young *et al.*, 2005). The total carbon stocks in the ET included estimates for soil using; 37 tC/ha, for C in soil beneath perennial pastures, and 28 tC/ha under predominantly annual grasslands. The C stock in pasture in both systems was estimated at 3 tC/ha.

2.5.2 Fullcam modelling for the determination of carbon stocks and sequestration rates. Carbon sequestration and stock estimates produced by FullCAM are highly dependent upon the input parameters, and in particular, the maximum above-ground biomass (M–value) parameter. This parameter represents the maximum possible biomass of the above-ground tree component of the model for each point on the property and is derived from a spatial layer that is supplied with FullCAM. This study used a mean maximum above-ground biomass layer value across the extent of each property. The M-value layer was sourced from the 2016 public release of FullCAM. Details of the model settings are provided in the Supplementary Material (Table C1).

Whilst the use of models to estimate carbon stocks and sequestration rates introduces a level of uncertainty compared to direct measurement of the EAs, the approach is consistent with Australia's use of FullCAM to model carbon sequestration under the ERF, and represents a practical balance in the cost vs. accuracy of the measurement for NCA.

2.6 Timeframes and reporting periods

ES such as carbon sequestration and environmental impacts such as GHG emissions and flows of pollution reported in the EP&L are measured as amounts generated between time periods (Brooke *et al.*, 2016). By convention, under International Accounting Standards (IAS) and SEEA EA, accounting is *ex-post,* and the reporting period for changes to NC (EAs) and flows of ES is usually a calendar or financial year. This is also the timeframe for reporting flows of environmental impacts in EP&L (Brooke *et al.*, 2016). Under IAS and SEEA EA, stocks of assets are measured at a point in time and the date of valuation is disclosed. While this study only measured NC stocks at one point in time, comparisons could be made with assessments at other dates to determine whether changes to NC have occurred.

3. Demonstration accounts

Ecosystem accounts and experimental inputs to the EP&L for the two contrasting farm enterprises are presented along with a brief narrative to assist with interpretation. The ecosystem accounts for each farm are presented with accounts of land condition for grazing presented first, followed by accounts of ET extent and then accounts of carbon stocks separately for each property. The rates of carbon sequestration and estimated inputs to the EP&L for both properties are provided in combined tables. To allow the NCA information to be interpreted, the accounts for each demonstration should be read with reference to the descriptions of the state (or transition) categories in the methods. These provide information about the typology and scales used to differentiate NC type and condition.

3.1 Farm 1 – ecosystem accounts

The condition of the land for grazing on Farm 1 was Very Good or Good (Table 4), indicating that the use of the NC resource base for livestock production is optimised for the corresponding landscape; the land used for grazing is both productive and sustainable.

The ET extent accounts (Table 5) suggest that healthy grassy woodlands that are EAs of Farm 1 are persisting and regenerating on a property-wide basis – they are either maintaining or improving in condition. A significant proportion of the property is judged to be transitioning towards states that are closer to the reference condition, rather than remaining static or degrading. While some areas of the property are presently missing some grassy woodland species, there is no evidence in any part of the property, other than areas of domestic use and infrastructure, of complete or permanent replacement of the grassy woodland ecosystem by a different type of ecosystem. This suggests that Farm 1 is not contributing to the extinction of grassy woodland species.

As a result of the significant presence of ecological functions and processes associated with grassy woodlands, Farm 1 stores a large amount of carbon (more than 220,200 tonnes) above and below ground (Table 6). A significant proportion (almost all) of the property is

	Land condition class (for grazing)						
Ecosystem type	Very good	Good	Fair	Poor	Very poor	NA	Totals
Derived pasture	409	0	0	0	0	0	409
Grassy woodland	2,154	697	0	0	0	65	2,916
Riparian	0	0	0	0	0	139	139
Domestic	0	0	0	0	0	3	3
Infrastructure	0	0	0	0	0	3	3
Property total	2,563	697	0	0	0	210	3,470

Notes: Units: hectares; NA refers to areas where it is irrelevant to apply a grazing condition class (i.e. infrastructure)

Table 4. Farm 1 – Natural Capital/land condition for livestock grazing at 15th January 2018

	State (or Transition) category						
Ecosystem type	T2A–1A	S2A	T2B–2A	S2B	T3B–2B	NA	Total
Derived pasture	0	0	0	409	0	0	409
Grassy woodland	626	976	967	271	77	0	2,916
Riparian	126	13	0	0	0	0	139
Domestic	0	0	0	0	0	3	3
Infrastructure	0	0	0	0	0	3	3
Total	752	989	967	680	77	6	3,470

Notes: T2A-1A is ecosystem units that are transitioning between State 2 A and State 1 A. T2B-2A is ecosystem units that are transitioning between State 2B and State 2 A. T3B-2B is ecosystem units that are transitioning between State 3B and State 2B; NA refers to areas such as infrastructure where it is irrelevant to apply a state or transition class

Table 5. Farm 1 – Natural Capital extent (ha) of each state and transition class (see supplementary materials for descriptions)

transitioning to a state closer to the reference condition described in the grassy woodlands STM – it is improving in condition. As described in the methods, natural tree regeneration and maturation and stocks of coarse woody debris (CWD), are associated with these transitions and, therefore, the areas that are transitioning to higher condition states are also adding to carbon stocks on the property.

3.2 Farm 2 – ecosystem accounts

The condition of the land for grazing on Farm 2 was Very Good or Good (Table 7). This indicates that the NC resource base for livestock production is optimised for the corresponding landscape; the land used for grazing is both productive and sustainable.

As expected, given the history of clearing, grazing management and nutrient enrichment, the NCA of Farm 2 reflects the removal and replacement of some of the natural grassy woodlands with pastures and agroforestry, and the relatively (to Farm 1) degraded state of the remaining woodland areas. Table 8 illustrates this by quantifying the substantial presence of grassy woodlands in State 3 A or 3B and the extensive investment in forestry on this property. Forestry and environmental plantings include assets that have fully replaced (FR) and partly replaced (PR) the grassy woodland ET. As a result of this investment, Farm 2 still exhibits ecological diversity and a significant range of EAs associated with the production of ES common to grassy woodlands, but does this via different types of EAs. The ES generated by the replacement assets include shade and shelter for livestock (Baker *et al.*, 2018) and habitat for a range of species, including birds and insects that are likely to provide pollination and pest predation services (Landis *et al.*, 2000; Lavorel *et al.*, 2015;

Table 6. Farm 1 – Carbon stock accounts (Mg C); na refers to areas where it is irrelevant to apply carbon storage figure (i.e. infrastructure)

Ecosystem type	State (or Transition) category						
	T2A–1A	S2A	T2B–2A	S2B	T3B–2B	NA	Total
Derived pasture	0	0	0	19,358	0	0	19,358
Grassy woodland	52,561	66,628	53,873	12,826	3,526	0	189,414
Riparian	10,596	856	0	0	0	0	11,452
Domestic	0	0	0	0	0	3	3
Infrastructure	0	0	0	0	0	3	3
Total	63,157	67,484	53,873	32,184	3,526	7	220,230

Table 7. Farm 2 – Natural Capital condition for livestock grazing at 15th May 2018

Ecosystem type	Grazing condition class						
	Very good	Good	Fair	Poor	Very poor	NA	Total
Derived pasture	309	12	0	0	0	0	321
Grassy woodland	80	28	0	0	0	2	110
Riparian	0	0	0	0	0	35	35
Exotic forest	107	1	0	0	0	27	135
Exotic shelterbelt	23	2	0	0	0	11	36
Native shelterbelt	0	0	0	0	0	12	12
Domestic	0	0	0	0	0	6	6
Infrastructure	0	0	0	0	0	1	1
Total	519	43	0	0	0	94	656

Notes: Units: hectares; NA refers to areas where it is irrelevant to apply a grazing condition class (i.e., infrastructure)

Table 8. Farm 2 – Natural Capital extent (ha) of each state and transition class for grassy woodland ecosystem types and classifications representing types of agroforestry assets at different levels of maturity, as described in Table 2 (see supplementary materials for additional descriptions)

	State (or Transition) category															
Ecosystem type	S3A	S3B	S4	S5	T2A-1A	T3A-2A	FRNDM[a]	FRNOY[b]	FREDM[c]	FREDI[d]	PR4BNOI[e]	PR3BEOI[f]	PR3BNOY[g]	PR3BEOY[h]	na	Total
Derived pasture	0	287	33	1	0	0	0	0	0	0	0	0	0	0	0	321
Grassy woodland	44	2	0	0	1	1	0	0	0	0	50	0	12	0	0	110
Riparian	0	7	0	0	0	0	0	0	0	0	29	0	0	0	0	35
Exotic forest	0	0	0	0	0	0	0	0	2	38	0	88	0	7	0	135
Exotic shelterbelt	0	0	0	0	0	0	0	0	8	19	0	9	0	0	0	36
Native shelterbelt	0	0	0	0	0	0	11	1	0	0	0	0	0	0	0	12
Domestic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6
Infrastructure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Total	44	296	33	1	1	1	11	1	10	56	78	97	12	7	7	656

Notes: [a]FRNDM (Fully replaced, native, dense with mature plantings); [b]FRNOY (Fully replaced, native, open planting, young trees); [c]FREDM (Fully replaced, exotic, dense plantings with mature trees); [d]FREDI (Fully replaced, exotic, dense plantings with intermediate-aged trees); [e]PR3BNOI (Partially replaced, groundlayer in State 3B, native, open plantings with intermediate-aged trees); [f]PR3BEOI (Partially replaced, groundlayer in State 3B, exotic, open plantings with intermediate-aged trees); [g]PR3BNOY (Partially replaced, groundlayer in State 3B, native, open plantings with young trees); [h]PR3BEOI (Partially replaced, groundlayer in State 3B, exotic, open plantings with young trees)

Makim, 2017). The active growth of forestry assets also provides carbon sequestration services.

As a result of the significant investment in agroforestry, Farm 2 has a considerable amount of carbon (over 42,000 tonnes) stored in the above and below-ground biomass (Table 9).

3.3 Carbon sequestration services

The two demonstration properties are generating carbon sequestration services (Table 10). Note, this is due to normal management operations by the landholders and is not an additional activity that would enable participation in carbon markets as presently structured.

The magnitude of the estimate of sequestration for Farm 1 reflects the large extent of grassy woodland that has been, and continues to be, managed to allow for significant natural tree regeneration on this property. It is expected that the annual sequestration rate will reduce once the grassy woodland areas reach an optimal configuration that, in the property owner's view balances the native biodiversity of the ecosystem with the productive potential, and the property owner consequently changes the management of these areas to maintain them in a more static condition to achieve those dual outcomes (an identified goal).

The magnitude of the estimate of sequestration for Farm 2 reflects the extensive tree planting and, to a lesser extent (to date), facilitated regeneration of native biodiversity in pastures. The estimated sequestration rate due to planted trees is expected to continue in the short to medium term as the property owner works towards the goal of having 35% cover for managed forest and habitat. New plantings as well as the ongoing maturation of existing plantings will contribute to this.

The sequestration rates for both properties are consistent with estimates of other agricultural properties with extensive tree planting (Doran-Browne *et al.*, 2016). This highlights the potential for different investments in tree planting and natural regeneration to be reflected in estimates of individual farm carbon sequestration services. As mentioned earlier, modelling suggests that carbon sequestration rates will decline over time and will substantially reduce as the farm managers reach their desired balance of tree cover, landscape function and livestock production. With the current configuration of woody ecosystems, this is likely to occur in the next 30–50 years.

It should be noted that the carbon being sequestered on each farm (shown in Table 10) cannot be used for trading carbon offsets under existing schemes in Australia. The estimates provided are not calculated using a current ERF-approved methodology, and the sequestration related to the regeneration of grassy woodlands and growth of agroforestry assets is unlikely to satisfy the "newness" requirement (CER, 2017) as currently applied. Furthermore, the sequestration activities of these farms as part of their enterprise operations imply no obligations for permanence, as required by the ERF.

3.4 Inputs to Environmental Profit and Loss statement

The inputs to the EP&L are summarised for both farms. Table 11 presents the detailed calculations of GHG emissions. Results for all EP&L factors including the GHG emissions estimate are presented in Table 12. EP&L factors represent negative environmental impacts – the higher the quantity, the greater the negative impact on the environment.

These results were then combined with the resource use estimates to estimate the physical inputs for the six key areas of impact in the EP&L, as shown in Table 13.

Table 9. Farm 2 – Carbon stock accounts (Mg C)

	State (or Transition) category															
Ecosystem type	S3A	S3B	S4	S5	T2A-1A	T3A-2A	FRNDM[a]	FRNOY[b]	FREDM[c]	FREDI[d]	PR4BNOI[e]	PR3BEOI[f]	PR3BNOY[g]	PR3BEOY[h]	na	Total
Derived pasture	0	12,993	1,373	17	0	0	0	0	0	0	0	0	0	0	0	14,384
Grassy woodland	2,176	86	0	0	99	61	0	0	0	0	0	2,802	585	0	0	5,809
Riparian	0	294	0	0	0	0	0	0	0	0	0	1,970	0	0	0	2,264
Exotic forest	0	0	0	0	0	0	0	0	462	5,298	6,826	0	0	341	0	12,926
Exotic shelterbelt	0	0	0	0	0	0	0	0	1,743	2,674	650	0	0	0	0	5,067
Native shelterbelt	0	0	0	0	0	0	1,496	70	0	0	0	0	0	0	0	1,565
Domestic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6
Infrastructure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Total	2,176	13,373	1,373	17	99	61	1,496	70	2,205	7,971	7,476	4,771	585	341	7	42,021

Notes: [a]FRNDM (Fully replaced, native, dense with mature plantings); [b]FRNOY (Fully replaced, native, open planting, young trees); [c]FREDM (Fully replaced, exotic, dense plantings with mature trees); [d]FREDI (Fully replaced, exotic, dense plantings with intermediate-aged trees); [e]PR3BNOI (Partially replaced, groundlayer in State 3B, native, open plantings with intermediate-aged trees); [f]PR3BEOI (Partially replaced, groundlayer in State 3B, exotic, open plantings with intermediate-aged trees); [g]PR3BNOY (Partially replaced, groundlayer in State 3B, native, open plantings with young trees); [h]PR3BEOI (Partially replaced, groundlayer in State 3B, exotic, open plantings with young trees)

Due to the nature of the operations on each farm, fossil fuel use is limited to small farm vehicles and tractors, and tools such as chainsaws. There is minimal mechanisation in the form of cultivation and fertiliser application on either farm, with a limited amount of forestry activities on each farm. As a result, GHG emissions are at the lower end of the range reported in other studies (25.1 ± 4.8 kg CO_2e/kg greasy wool; Wiedemann *et al.*, 2016), and air pollution from fuel particulate matter is judged to be negligible.

The seasonal ground cover imagery statistics produced for both demonstration farms using FarmMap4D are consistent with the observations of the field ecologist in the NCA, indicating that both farms maintain ground cover significantly above the threshold for vulnerability of soil to wind and water erosion and neither farm employs cultivation that would cause air pollution from dust.

Both farms use minimal chemicals in their operations and limited fodder is purchased for livestock. When used, fodder is in the form of large bales of hay and, accordingly, they were assessed as producing negligible waste. As discussed earlier in the ecosystem accounts, both farms have pastures and riparian areas in Very Good or Good condition; this protects waterways from chemical pollution and soil from water erosion. There is no irrigation for pasture production; thus, water use (normalised stress-weighted water consumption) reflects consumption by livestock and evaporation of water from dams.

Table 10.
Carbon sequestration services produced by farm 1 and farm 2

Bio-carbon stocks and sequestration	Unit	Farm 1 (3470 ha)	Farm 2 (656 ha)
Estimated Carbon Stocks across whole farm	Mg C	220,230	42,021
Estimated Carbon Stocks per hectare	Mg C/ha	63.5	64.0
Estimated C sequestration across whole farm[a]	Mg C/year	−3,252	−320
Estimated $C0_2$e sequestration per year over whole farm[a]	T CO_2e/year	−11,925	−1,172

Note: [a]A negative value represents removal of CO_2 from the atmosphere

Table 11.
Annual inputs and production characteristics (averaged over period). GFW – greasy fleece weight. WTA - withdrawal to availability ratio

Parameter	Unit	Farm 1	Farm 2
Collection period	NA	2007/08 – 2016/17	2011/12 – 2016/17
Mean annual max temperature	Degrees C	19.4	19.6
Water stress index	WTA	0.0208	0.0208
Percentage of stock water sourced from dams	%	5	10
Property size	Ha	3,470	656
Breeding ewes joined	head	2,650	1,874
Adult wethers	head	265	134
Sheep replacement rate	%	25	25
Lamb weaning rate	%	90	90
Clean wool yield (% greasy)	%	75	73
Fibre diameter	μm	16.5	16.5
Wool produced	kg GFW	16,153	12,409
Proportional allocation of inputs to sheep products	%	37.8	85.1
Biophysical allocation to wool	%	41.7	41.7
Breeding cows joined	head	444	29
Cattle replacement rate	%	14	22
Calving rate	%	95	98
Fertiliser allocation to livestock production	%	100	100

Parameter	Farm 1	Farm 2
Energy emissions (t CO_2e)		
CO_2, CH_4, N_2O from petrol and diesel use	22.9	22.1
CO_2 from Electricity use	4.1	9.4
Fertiliser and other amendment emissions (t CO_2e)		
N_2O from fertiliser application (includes atmospheric deposition and leaching and runoff)	0.0	1.7
CO_2 from Lime and Urea application	0.0	0.0
Animal emissions (t CO_2e)		
CH_4 from sheep (enteric, manure management)	1,016.1	701.9
N_2O from sheep (urine and dung, atmospheric deposition, leaching and runoff)	68.2	47.0
CH_4 from cattle (enteric, manure management)	1,268.5	94.4
N_2O from cattle (urine and dung, atmospheric deposition, leaching and runoff)	49.9	3.8
Pre-farm emissions (t CO_2e)		
Fertiliser and other amendments	0.0	0.4
Fodder	8.6	9.3
Diesel and petrol	1.2	1.1
Sheep purchases	3.2	69.0
Cattle purchases	30.4	0.1
Total Emissions (t CO_2e)	2,473	960

Table 12. Annual estimates of farm greenhouse gas emissions (averaged over time period); CO_2e – carbon dioxide equivalents

Metric	Unit	Farm 1	Farm 2
Air pollution	kg pollutant/kg greasy wool	negligible	negligible
Greenhouse gas emissions	kg CO_2e/kg greasy wool [5]	28.4	28.7
Waste	kg waste/kg greasy wool	negligible	negligible
Normalised stress weighted water consumption (including evaporation)	litres H_2Oe/kg greasy wool [6]	2.6	3.0
Water pollution	kg N/kg wool	negligible	negligible
Land-use	Hectares allocated to wool production based on proportional allocation of area for sheep grazing and biophysical allocation to wool	534	224
Ecosystem service loss: Bio-prospecting and medicinal plants, Cognitive and learning opportunities, Disease and pest control, Fibre, other raw materials, Food from natural/semi-natural ecosystems, Ornamental products, Pollution control and waste assimilation, Recreation, Spiritual and aesthetic	Percentage of estimated ecosystem service loss based on average of biomass loss and species richness loss proxies	29%	48%
Ecosystem service loss: Air purification, Domestic and industrial water, Erosion control, Flood control and protection from extreme events, Stable climate	Percentage of estimated ecosystem service loss based on biomass loss proxy	26%	41%

Table 13. Experimental inputs to EP&L for both demonstration farms

The differences in estimates for land use change reflect the different configurations of the two farms. Farm 1 has a large extent of original grassy woodland biome; thus, it is estimated that 71–74% of the original ES are being delivered by the farm despite its use for wool production. In comparison, the more highly modified configuration of Farm 2 resulted in an estimation that 52–59% of the ES of the original grassy woodland biome are provided by the farm.

As described earlier, the EP&L does not include estimates of carbon storage or sequestration. To provide a more complete and fair picture of the environmental performance of the farms, Table 14 summarises the GHG emissions and sequestration for each demonstration farm to show the net GHG performance of the two enterprises.

In summary, the accounts for both farms indicate that:

(1) The NC of both properties is mostly in very good condition for grazing.
(2) Farm 1 is contributing significantly to the persistence of grassy woodland ecosystems.
(3) As a consequence of the extensive investment in timber plantations and environmental plantings, Farm 2 is significantly contributing to the generation of many ES that would be delivered by natural grassy woodland ecosystems.
(4) Both farms are presently sequestering significant amounts of carbon based on current management practices and ecosystem conditions. In CO_2e terms, the sequestration rates for both farms exceed their emissions.

4. Discussion

4.1 How primary producers can be included in estimates of environmental performance of apparel supply chains

Our work is the first, to our knowledge, to demonstrate how individual farm businesses can compile information about their NC and environmental performance for inclusion in both EP&L estimates and national and regional accounts under the SEEA EA.

The development of an accounting framework for environmental performance and NC at the farm level is an essential first step in quantifying the comparative performance of supply chains and providing empirical evidence for evaluation of the capacity of environmental accounting and performance reporting to improve environmental performance (Deegan, 2017; Gray, 2010). While this paper focuses on wool, the methods used are also suitable for sheep meat supply chains.

In addition to providing information useful for supply chains, the fine scale of this information can inform farm management decisions. The very detailed breakdowns of GHG emissions (for example, Table 12) showing the individual sources of emissions may be used

Table 14. Estimated net greenhouse gas emissions and sequestration rates

Metric	Unit	Farm 1 (3470 ha)	Farm 2 (656 ha)
On farm emissions (excludes pre-farm emissions)	t CO_2e/year	2,430	880
Estimated CO_2e sequestration per year[a]	t CO_2e/year	−11,925	−1,172
Net GHG balance for on-farm operations [a]	t CO_2e/year	−9,495	−292

Notes: [a]A negative value represents removal of CO_2 from the atmosphere. A natural capital accounting framework to communicate the environmental credentials of individual wool-producing businesses by farm managers to make operational changes to improve performance. The presentation of information on a per kilogram of product basis, as recommended by the United Nations (UNCTAD, 2016), allows comparison of the environmental performance of different products, thus providing insights about how a change to production types may influence environmental performance. However, this may incorrectly penalise luxury goods such as fine wool, and alternate measures should be considered to ameliorate this problem (Wiedemann *et al.*, 2019).

Comparisons of the performance of different farms can also be supported by the approach described in this paper. Comparisons of the environmental performance of different farms need to control for environmental factors such as rainfall, soil type and production type. The compiled contextual information about the farm (Table 11) provides this required information.

Our use of STM to quantify NC demonstrates how methods developed for the scientific study of the health and sustainability of ecosystems can provide scientifically coherent and holistic quantification of NC on farms. This approach is not limited to wool-producing farms. STM models of a biome are coherent with the typology described in the SEEA EA which is required for compiling aggregated accounts at the catchment, region and national scales for use in economic and land use policy design and planning. Thus, the use of STM simultaneously allows for the compilation of fine-scale information to describe the farm-scale NC and aggregation to regional or national accounts. By providing empirical evidence to improve the accuracy of agricultural ES and biodiversity loss estimates we have demonstrated a way to significantly improve the faithfulness of EP&L factors for land use and biodiversity. This approach has the potential to enable empirical measurement of the contemporary management of biodiversity and ES by wool growers in different countries so as to compare performance.

The inclusion of areas transitioning between stages in the STM typology, e.g. for grassy woodlands in Farm 1 and different ages of agroforestry in Farm 2, demonstrates a way to use single point-in-time assessments to convey the likely trajectory of ecosystem change on a farm. As significant changes to some types of NC take a long time to occur, this indicator of the future condition of the NC of the farm can assist stakeholders to understand whether the NC on a farm is likely to be degrading, sustained or regenerated.

4.2 Challenges and opportunities in preparation and use of the information

Several challenges and opportunities were revealed in preparing the information.

While it was possible to compile farm-level EP&L inputs using data already collected by farmers, this was a manual process requiring detailed analysis of financial and operational records for use in calculations. If software packages already used by farm businesses for financial and management accounting could be modified to enable automated output of environmental performance information, this would reduce the cost of compilation and improve the accuracy.

Not all information required by the EP&L was able to be estimated using information available to farmers. Measurement of air pollution from fuel use requires information about fuel quality, vehicle type and age, which is not routinely published. Accordingly, accurate compilation of farm-level air pollution cannot be performed unless local fuel suppliers and vehicle manufacturers publish this information.

To estimate carbon storage and sequestration rates, we applied methods currently used for Australia's national GHG inventory. The application of these at the farm level revealed that these need further development to present a faithful representation of farm performance. Three issues were observed. The M-value layer of FullCAM at different points within the properties and between the properties resulted in carbon stock and sequestration rate estimates that were not consistent with the on-ground assessments of the ecologist teams who assessed the NC type and condition of the farms. Thus, ecosystem accounting assessments of NC type and condition could be utilised to calibrate and continually improve models such as FullCAM.

Existing ERF methodologies require modelling of each EU or non-contiguous asset, and this is not practical when modelling carbon sequestration across a diverse farming enterprise. This could potentially be solved by developing "lookup tables" for carbon and other attributes of different types of NC to make the accounting process easier. For example, empirical assessments of ecosystem characteristics, such as those described in the STM of this study, may be linked with "coefficients" describing their carbon sequestration and storage; this would make accounting for these attributes relatively straightforward. A similar approach could be used to associate NC of different types and conditions with attributes such as biodiversity and capacity to generate ES such as pollination and pest predation.

The approach described here of using the STM to determine sequestration rates highlights the potential for future research to establish "lookup tables" to calibrate FullCAM models via direct measurement of biomass (Approach 1 in Methods).

Estimates from tools such as FullCAM are sensitive to the input parameters and the ET and condition. We observed that estimates of sequestration rates on a per kg of wool basis magnified this sensitivity, especially for cases where estimates were close to carbon neutral. To be confident that estimates of carbon sequestration for different agricultural properties are comparable, standards for setting these parameters must be developed or the detailed parameters used in estimations must be disclosed to users of the information to help them determine their confidence in the estimations.

Finally, in reflecting on the presentation of the information via the terminology and codes presented in the summary tables, the lack of familiarity with NC in biophysical terms may make it difficult to interpret the information. This could be addressed with training and practice.

4.3 Future policy needs

The following topics require further research and policy development.

The two demonstration accounts illustrate two farm businesses that are improving their NC and exhibiting good environmental performance, including net sequestration of GHG and investment in biodiversity, in the absence of formal contracts with external parties. That is, their performance on these environmental issues is not 'additional' to their normal management.

Recent guidance for EP&L compilers (Brooke *et al.*, 2016) indicates that environmental "profits" can only be accounted by a company if improvement is additional and in response to a deliberative investment. It is not presently clear in the EP&L guidance whether companies that change wool suppliers to source wool from producers with superior environmental performance can account these improvements as additional and in response to deliberative investment, and thus, as an environmental "profit". The strict interpretation of additionality and deliberative investment may mean that an environmental "profit" can only be accounted if the wool grower demonstrates a change in performance as a result of supply chain investment. It seems somewhat perverse to exclude high-performing producers from being rewarded and recognised for their performance. Future guidance for EP&L (and other standards) should consider how to account for this.

The question of accounting for carbon sequestration presents a similar problem. At present, in Australia, the only way primary producers can be recognised for carbon sequestration is to participate in formal contracts, such as the ERF (www.cleanenergyregulator.gov.au/erf). Farms that have been sequestering carbon in amounts greater than their GHG emissions should be able to be recognised for their positive contribution to mitigating climate change, even if they do not participate in formal contracts to do so. Our SEEA EA-coherent ex-post demonstration (Ajani *et al.*, 2013; Keith *et al.*, 2021; UNCEEA, 2021b) of NC accounts for the two farms may provide a practical way to do so.

Finally, even if future research and technology reduce the cost of compiling farm-level information to be used in estimation of the environmental performance of supply chains and regions, a cost to farmers will remain. Considerations should be given to formalising cost-sharing by members of the supply chain and governments who stand to benefit from the preparation of this information.

5. Conclusion

We have demonstrated an approach to NC accounting that is suitable for preparing inputs for environmental performance reporting of supply chains and that can communicate whether individual producers are sustaining, improving or degrading their NC. Measurements suitable for the estimation of supply chain performance can simultaneously produce information useful for farm management and for assessment of the performance of regions.

The inclusion of individual primary producers in EP&L and SEEA EA is largely possible with existing methods of measurement. The combination of EP&L and NCA frameworks for the assessment of farm performance allows farm businesses to estimate, communicate and improve their NC and environmental performance. The methods used are likely to meet the needs of other frameworks in addition to EP&L, and should assist sustainability-conscious supply chains to more accurately assess the environmental performance of their wool producers and use these assessments in selective sourcing strategies to improve supply chain performance. Empirical measures of environmental performance and NC condition have the potential to enable evaluation of other sustainability accounting frameworks by providing ways to verify their effectiveness in inducing businesses to reduce their environmental impacts and improve the condition of their NC. However, further research is necessary.

To establish a faithful view of the environmental performance of an individual enterprise, the accuracy of modelled estimates of farm-scale carbon sequestration, GHG emissions and biodiversity needs improvement. Further research is also needed to develop methods for the quantification of air pollution generated by farm businesses. Development or modification of technology to reduce the cost of data acquisition is also needed to enable widespread use.

Two main policy developments are suggested concerning the inclusion of primary producers in the sustainability and environmental performance reporting of supply chains. Firstly, we note the considerable time and expense for producers to prepare this information. Governments and members of the supply chain should acknowledge the value of this information to their organisations and consider sharing some of the cost of its preparation with primary producers. Secondly, there is the potential for adverse outcomes associated with the "additionality" requirement in EP&L for reporting environmental profit. Thus, standard-setters should develop policies and guidance for accounting for already good environmental performance and NC investment when it is not "additional" to the farmer's normal management.

Finally, to support progress without constraining debate about whether sustainability reporting should be standardised, future research and policy investments should enable the acceleration of publicly available standards for farm-scale empirical measurement of the common elements of sustainability reporting, including GHG emissions, energy use, water consumption (use), water and air pollution and waste generation, as well as empirical measures of biodiversity, ES, carbon sequestration and storage services by primary producers.

A Current canopy estimate derived using the i-Tree canopy tool (https://canopy.itreetools.org/), selecting a representative polygon in the local area, and undertaking 100 samples

B 1860 is used to simulate the bulk clearing undertaken during early colonisation and settlement of Australia by Europeans.

Simulation of the regeneration of an existing remnant woodland was achieved by combining the base plot and woodland regeneration plot using a logistics function to model the gradual recruitment of new trees over time, with a slow start to the recruitment (when the woodland was sparse) and faster recruitment as the woodland becomes denser (D. O'Brien, unpubl.).

The max-AGB (maximum above ground biomass) used for this study was calculated as the mean for each farm using QGIS (www.qgis.org/en/site/), and the published spatial data set for Site potential (M) version 1.0 (https://data.gov.au/data/dataset/emissions-reduction-fund-environmental-data/resource/5814a7c7-3890-40ca-a946-3fd43d341b8d?inner_span=True).

The M values used in the models were 104.787 and 130.139 DM/ha, respectively, for Farms 1 and 2, with a coefficient of variance of 24% and 5%, respectively.

The resulting sequestration rates for each of the states and transitions for both farms are provided in Table C2.

Notes

1. The dry sheep equivalent (DSE) is commonly used in agriculture as a standardised unit to enable comparison of farms with different types of animals.
2. Seasonal ground cover statistics provide information about the proportion of land that has no ground cover (is bare), the proportion of land that is covered with dry vegetation, and the proportion that is covered by green vegetation. Statistics are available from 1989 for most regions in Australia.
3. Ex-post means "after the event", as compared to ex-ante, meaning "before the event". From a financial perspective, it is the difference between reporting what has happened vs what is predicted to happen.
4. FullCAM is a freely available software system for tracking GHG emissions and changes in carbon stocks associated with land use and management in Australian agricultural and forest systems. It is applied at the national scale for land sector GHG emissions accounting (Australian Government 2018), and at the local scale for monitoring and reporting carbon sequestration projects, such as revegetation and the management of regrowth.
5. Kering's EP&L inputs are reported as per kilogram of clean wool for each of the metrics across each tier of the supply chain, rather than per kilogram of greasy wool as reported in this table. This allows the total emissions to be determined across all tiers of the supply chain. Reporting the case study results in terms of emissions per kilogram of clean wool results in emission intensities of 39.7 and 39.4 kg CO_2-e/kg wool for Farms 1 and 2, respectively. Note that this does not account for emissions relating to the scouring process, or allocation to wool grease. Those emissions would be accounted for in the Tier 3 (Raw Material Processing) analysis.
6. Normalised stress-weighted water consumption per kilogram of clean wool for Farms 1 and 2 was 3.5 and 4.1 litres H_2O-e/kg wool, respectively. This does not account for water use during wool scouring as part of the processing from greasy to clean wool.

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Appendix 1. State and transition models

Title/code for 'state'	Brief description	Detailed description
1A	Grassy woodland with a very diverse native ground-layer	Tree (canopy) cover >50% and the ground-layer has a high diversity and cover of native species (> 30 species and >70% groundcover of native species). Never fertilised or fertiliser use ceased 3–4 decades previously
1B	Derived native grassland with a very diverse native ground-layer	There is low tree canopy cover, but the ground-layer has a high diversity and cover of native species (> 30 species and >70% groundcover of native species). Never fertilised or fertiliser use ceased 3–4 decades previously
2A	Grassy woodland with a diverse native ground-layer	Tree canopy cover is slightly lower than 1 A (20–35%) and the ground-layer has a slightly lower diversity and cover of native species compared to 1 A (16–29 species and 50–69% groundcover of native species). Rarely fertilised or fertiliser use ceased 2–3 decades previously
2B	Derived native grassland with a diverse native ground-layer	There is low tree canopy-cover (5–9%), but the ground-layer has a good diversity and cover of native species (16–29 species and 50–69% groundcover of native species). Rarely fertilised or fertiliser use ceased 2–3 decades previously
3A	Some mature remnant trees present and a moderately diverse, mainly native, ground-layer	Mature remnant eucalypts present but with no tree regeneration. The ground-layer has a moderate diversity of native species (8–15 species) and 30–49% native-ness of the ground-layer. Some exotic species are present. Historically low-moderate fertiliser application. Most recent fertiliser application may have been within past five years
3B	A moderately diverse and mainly native grassland with few trees	Few mature eucalypts present (but with no tree regeneration). The ground-layer has a moderate diversity of native species (8–15 species) and 30–49% native-ness of the ground-layer. Some exotic species are present. Historically low-moderate fertiliser application. Most recent fertiliser application may have been within past five years
4	Grassland a mix of native and exotic species and occasional scattered trees	Grassland with 4–7 native species, <30% cover of native species and the occasional remnant tree with no natural tree regeneration. There has been frequent fertiliser application until present day
5	Predominantly exotic grassland with a few native species. No remnant trees present.	No remnant trees remaining and no natural tree regeneration. Pastures are predominantly exotic with <3 native species and <10% cover of native species. There has been frequent fertiliser application until present day

Notes: Transitions between states are also applied to the individual ecosystem assets. Model adapted from the simplified Box Gum Grassy Woodland State and Transition model in Whitten *et al.* (2010)

Table A1. Grassy woodland states reflecting the degree and permanence of anthropogenic disturbance and intensification are used to describe EA

Appendix 2. Emissions factors and uncertainty estimates

Emission source	Key parameters/model	Uncertainty
Enteric CH_4 - sheep (pastured)	Intake (kg DM / head/day) × 0.0188 + 0.00158	± 25%
Enteric CH_4 - cattle (pastured)	Intake (kg DM / head) × 20.7/1000	± 25%
Manure CH_4 (temperate climate)	0.003 kg CH_4 / kg dry matter manure	± 55%
Manure N_2O	0.004 kg N_2O-N / kg N in urine and faeces	± 55%
Synthetic Fertiliser N_2O	0.002 kg N_2O-N / kg N applied	± 56%
Organic Fertiliser N_2O	0.01 kg N_2O-N / kg N applied	± 56%
Atmospheric deposition (Synthetic Fertiliser) N_2O	0.11 kg N / kg N applied	± 56%
Atmospheric deposition (Organic Fertiliser) N_2O	0.21 kg N / kg N applied	± 56%
Atmospheric deposition (manure, urine, faeces) N_2O	0.21 N / kg N applied	± 56%
Indirect nitrous oxide from leaching and runoff	0.24 kg N leached / kg N applied	± 56%
	0.011 kg N_2O-N / kg N leached or in runoff	± 56%
Lime application CO_2	0.12 * 0.9 kg CO_2 / kg limestone applied	± 54%
Urea application CO_2	0.2 kgCO2/kg urea applied	± 51%

Table A2. Emissions factors for the calculation of GHG emissions, including the uncertainty estimates of the factors (DISER 2020a)

Appendix 3. FullCAM model settings

Table A3. FullCAM model settings

Model name	Base plot	Woodland regeneration	Native plantings - blocks	Native plantings - belts	Exotic forestry
Purpose	Model used to determine the base for remnant vegetation in the woodland areas	Model used to determine the additional growth from regeneration of existing woodland assets	Used to model the carbon stocks in native plantings in fully replaced block plantings	Used to model the carbon stocks in native plantings in a shelter belt configuration	Used to model the carbon stocks in exotic plantings/ forestry in fully replaced systems
Type	Forest system	Forest system	Forest system	Forest system	Forest system
Tree yield formula	Block - regeneration systems	Block - regeneration systems	Block - regeneration systems	Belt plantings < 500 sph	Long rotation plantations
Tree species	Eucalyptus Open Woodland	Eucalyptus Open Woodland	Mixed species environmental planting	Mixed species environmental planting	Pinus radiata
Latitude/ Longitude	Mid-point of the property	Mid-point of the property	Mid-point of the property	Mid-point of the property	Mid-point of the property
Max AGB	Property mean	Property mean	Property mean	Property mean	Property mean
Water/ productivity extrapolation	Cycle table data across time	Cycle table data across time	Cycle table data across time	Cycle table data across time	Cycle table data across time
Initial conditions	Default	Trees: none Standing dead: none Debris: as per 12/ 1999 values from base plot Soil: as per 12/ 1999 values from base plot	Trees: none Standing dead: none Debris: as per 12/ 1999 values from base plot Soil: as per 12/ 1999 values from base plot	Trees: none Standing dead: none Debris: as per 12/ 1999 values from base plot Soil: as per 12/ 1999 values from base plot	Trees: none Standing dead: none Debris: as per 12/ 1999 values from base plot Soil: as per 12/ 1999 values from base plot
Start simulation	January 1400	January 2000	January 1400	January 1400	January 1400
End simulation	January 2400	January 2400	January 2400	January 2400	January 2400
Events	Plant trees @1/1/ 1400	Plant trees (Eucalyptus	Plant trees (mixed species	Plant trees (mixed species	Plant trees (Pinus radiata)

(continued)

Table A3.

Model name	Base plot	Woodland regeneration	Native plantings - blocks	Native plantings - belts	Exotic forestry
	Fire regime (Forest fire 51-61_64-70_NSW-Wildfire) every 80 years to present Thin to current canopy cover estimateA@ 1/1/1860B	Open Woodland) @1/1/2000	environmental planting on land manage for environment) @1/1/2000	environmental planting: Belt plantings < 1500 sph) @1/1/2000	@ 1/1/2000 including starter fertiliser and weed control events Standard NSW plantation management regime of: Prune 33% @ year 7 Thinning 61.5% @ year 13 Thinning 33.3% @ year 17 Thinning 39.9% @ year 26 Thinning 50% @ year 30

State	Farm 1	Farm 2	State	Farm 1	Farm 2	State	Farm 1	Farm 2
S1A	−0.32	−0.34	T2A–2B	0.89	1.08	FRNDM	N/A	−0.28
S1B	−0.51	−0.66	T2B–2A	−0.89	−1.08	FRNDI	N/A	−1.12
S2A	−1.15	−1.41	T3A–3B	0.41	0.55	FRNDY	N/A	−3.18
S2B	−0.51	−0.66	T3B–3A	−0.41	−0.55	FRNOM	N/A	−0.28
S3A	−0.51	−0.66	T4–5	0.05	0.05	FRNOI	N/A	−1.12
S3B	−0.30	−0.44	T5-4	−0.05	−0.05	FRNOY	N/A	−3.18
S4	−0.10	−0.09	T1A–2A	1.17	1.42	FREDM	N/A	−2.15
S5	0.00	0.00	T2A–1A	−1.17	−1.42	FREDI	N/A	−0.76
NA	0.00	0.00	T1B–2B	0.00	0.00	FREDY	N/A	−4.37
			T2B–1B	0.00	0.00	FREOM	N/A	−2.15
			T2A–3A	0.89	1.08	FREOI	N/A	−0.76
			T3A–2A	−0.89	−1.08	FREOY	N/A	−4.37
			T2B–3B	0.41	0.55	PR3BNOM	N/A	−0.72
			T3B–2B	−0.41	−0.55	PR3BNOI	N/A	−1.56
			T3A–4	0.30	0.44	PR3BNOY	N/A	−3.62
			T4–3A	−0.30	−0.44	PR3BEOM	N/A	−2.58
			T3B–4	0.20	0.26	PR3BEOI	N/A	−1.20
			T4–3B	−0.20	−0.26	PR3BEOY	N/A	−4.81

Table A4.
Sequestration rates ($Mg\ C\ ha^{-1}\ year^{-1}$)

Notes: Negative numbers represent removal of C from the atmosphere. Note that the sequestration rates for partially replaced states (PR3Bxxx) are adjusted by a factor based on the density of the ecosystem unit – ranging from 20% to 40% in our demonstration farms depending upon the asset in question

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