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# Accounting for carbon stocks and flows: storage and sequestration are both ecosystem services

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## Abstract

Ecosystem accounting methods must ensure comprehensiveness and mutual exclusivity, but also provide the data needed to support regional, national and international policies. In the case of carbon accounting, data are needed to identify options for mitigation activities and assess their relative benefits, as well as trade-offs between different ecosystem services. To achieve this objective, the carbon in all ecosystem assets and services, as well as their changes over time, must be included in a way that demonstrates their ability to maximize stocks in the biosphere, as this is the benefit for human well-being as a collective good.

The objective of climate change mitigation is to minimize the carbon stock in the atmosphere by maximising carbon stocks in the biosphere. A new approach is needed for the provision of information based on comprehensive accounting of carbon stocks and flows between the biosphere and atmosphere, which demonstrates the full suite of potential activities for reducing degradation and gaining benefits from carbon stocks in ecosystems.

The main issues that currently need to be addressed by accounting methodologies for carbon include: (i) carbon storage and sequestration of carbon are two distinct ecosystem services that should both be included, (ii) reference level of carbon stocks in ecosystems should be defined as the carbon carrying capacity, (iii) change in carbon stocks should be assessed against this baseline, rather than annual flows, (iv) classification of ecosystem types should recognize the differing qualities of carbon stocks, (iv) longevity as well as magnitude of carbon stocks is counted, and (v) risks of loss by natural and anthropogenic disturbance are quantified.

We demonstrate how enhancing current carbon accounting approaches to be comprehensive (i.e. all carbon stocks and flows are in an accounting framework), meets the standards required for accounting and also provides the information relevant to support policies and targets for climate mitigation objectives and ecosystem management. An integrated carbon account, combining information from the System of Environmental-Economic Accounting (SEEA) ecosystem accounts and the central framework, shows the relationships between asset tables, and the flows of natural inputs, products, residuals and ecosystem services. Both carbon storage and sequestration provide benefits, and we demonstrate in theory as the role of each as ecosystem services, and in practice reporting data in a comprehensive accounting framework of carbon stocks and flows.

## Issues and questions for discussion

1. Suggestions about the definitions and recording of the integrated accounting structure presented for carbon stocks and flows.
   a) accounting structure, including theoretical and technical elements
   b) formats that best meets policy needs
   c) further developments for integration of accounts

2. What is the relationship between accounts for carbon stocks and flows and ecosystem services?
   a) We propose that carbon storage and carbon sequestration are both ecosystem services, so that their distinct benefits are transparent.

   b) Many regulating services, including carbon storage, provide benefits derived from the existence of an ecosystem asset that may not have a current transaction value but does have a future benefit. Should these cases be defined as ecosystem services? If not, then how can these benefits be included in comparisons with other ecosystem services? Combining ecosystem services, such as carbon and biodiversity, is important for informing policy.

   c) Would inclusion of the value of externalities within the accounting framework help solve the issue for recognizing the benefits of carbon storage, as well as many other assets?

   d) How are the differences in qualities of carbon stocks, determined by the characteristics of their reservoirs, best included in the accounting framework to show risk of degradation, or conversely, capacity to supply future benefits?

3. Carbon storage and sequestration represent different components of the carbon cycle, and so provide different types of ecosystem services, and hence should use different valuation methods. What are the advantages and disadvantages of the methods listed or other suggested methods?

## Introduction

The objective of climate change mitigation is to maximise carbon storage in the biosphere. The Paris Agreement stated:

> *"Parties should take action to conserve and enhance, as appropriate, sinks and reservoirs of the greenhouse gases, including forests"* (Article 5, UNFCCC 2015).

This means that carbon stocks and the role of ecosystem processes in the conservation of carbon stocks are included, *"noting the importance of ensuring the integrity of all ecosystems, including oceans, and the protection of biodiversity"* (Preamble, UNFCCC 2015). REDD+ noted the "*role of conservation … and enhancement of forest carbon stocks*" (IPCC 2014).

Current carbon accounting for Land Use Land Use Change and Forestry (LULUCF) under the Kyoto Protocol (IPCC 2006) focusses on flows of greenhouses gases from and to sources and sinks. This accounting obscures the carbon stocks in ecosystems, their distribution, quality of the reservoirs, and hence actions that may positively or negatively affect them. The global goals for mitigation cannot be met without a significant contribution from carbon storage in ecosystems, particularly forests as well as peatlands, wetlands and mangroves (IPCC 2019). However, a new approach is needed for the provision of information relevant to these policies, based on comprehensive accounting of carbon stocks and flows between the biosphere and atmosphere. Such accounts will demonstrate the full suite of potential activities for reducing degradation and gaining benefits from carbon stocks in ecosystems.

The way benefits from ecosystems are defined, measured and reported in accounting systems has major implications for how ecosystems are perceived and managed. Many current accounting systems and policy negotiations regarding mitigation activities do not report comprehensively, including assigning the ecosystem service of carbon sequestration as a net annual flow into ecosystems, but not including the longevity of the stock and hence not recognising the benefit of long-term storage. Including only flows in reporting for the Kyoto Protocol (IPCC 2006) has resulted in incentives for promoting growth in young forests rather than protecting the larger, and more stable, carbon stocks in old forests.

The ecosystem service, as defined by Common International Classification of Ecosystem Services (CICES2016), is climate regulation. This is achieved by numerous ecosystem processes, including both stocks and flows, which can be increased or decreased by different human activities. Critically, assessing mitigation benefits must incorporate both the magnitude and longevity of stocks in calculating the average carbon stock over time, and the opportunity cost of foregoing the carbon storage in natural ecosystems. Optimum forest management for climate mitigation has been considered a trade-off between maximising carbon stocks and maximising sequestration rates (IPCC 2019). However, if both storage and sequestration are recorded as ecosystem services then their different benefits can be recognized and accounts can reveal past trade-offs and allow decision makers to assess the cost and benefits of future trade-off under different scenarios and policies.

Mitigation benefits of carbon storage in the biosphere are determined by the magnitude, longevity and stability of the carbon stocks, and the timing of the storage (Ajani et al. 2013, Mackey et al. 2015). Magnitude of carbon stocks depends on the net ecosystem carbon balance (or rate of sequestration) as well as the residence time of the carbon stock in the reservoir. Longevity refers to the average carbon stock in the ecosystem across the landscape and includes the effects of disturbance and regeneration. Stability of carbon stocks depend on maintenance of ecosystem integrity, which involves their composition, structure and function. Conversely, the risk of loss of carbon from the biosphere and emissions to the atmosphere depend on the resilience of ecosystems and their capacity for self-regeneration. Mitigation benefit in terms of timing of carbon storage refers to the fact that current carbon storage has greater benefit than carbon sequestration to accumulate stocks in the future, because losses occur rapidly but future sequestration is slow (Körner 2003). Maximum mitigation benefits derived from accumulation of carbon in resilient ecosystems providing long-term storage (Moomaw et al. 2019), have not been recognised fully compared with the flow derived from annual net primary productivity (IPCC 2019).

With continuing negotiations about rules and guidance to implement the Paris Agreement, together with the revision process for the SEEA Experimental Ecosystem Accounts, it is now a critical time to re-consider how carbon accounting systems can best meet the objective of maximising carbon storage in the biosphere. Assessment of ecosystems and land use activities should be based on characterising their carbon stocks in terms of their risk of loss from the biosphere to the atmosphere.

We describe how enhancing current carbon accounting approaches to be comprehensive of all stocks and flows, and within the context of ecosystem assets and services, can better inform land management decisions. The benefits provided by ecosystems can be recognised more fully, thus preventing perverse outcomes resulting from some emissions or removals not being counted, and allowing gains from the carbon sequestration potential of ecosystems. To show this, carbon accounts were developed from measured stocks and flows in a case study for a temperate eucalypt forest in Australia. These accounts illustrate the necessity to quantify stocks and flows using a reference level of the natural state in order to evaluate the relative benefits of current carbon storage, future sequestration under different management scenarios, the risk of carbon stock loss, and the opportunity cost of future sequestration potential.

## Opportunities from accounting systems

National and international climate change mitigation policies offer opportunities to incentivise change in land management activities that provide multiple environmental, social and economic benefits (Golub et al. 2009). Main international policy frameworks are listed in Table S1 with their potential use of information from carbon accounts. However, identifying and attaining the interrelationships between these multiple benefits depends on the accounting structure and data used. Designing the accounting framework is thus critical and a chance to move from what Vardon et al. (2016) described as an ‘accounting push’ to a ‘policy pull’.

Revision of the SEEA ecosystem accounting is an opportunity to provide a single, standardised system to support international conventions and national policies, that is, a methodology for reporting, setting targets, and evaluating options. Presentation of data in accounts show fundamental connections through dependencies of economic and human activity on the condition and services provided by ecosystems, and conversely, the impacts of these activities on ecosystems and their future capacity. Additionally, connections are revealed among components within ecosystems, such as habitat loss and fragmentation, greater climate variability, decline in ecosystem function, reduction in biodiversity, resulting in increased risk of loss of carbon stocks in vegetation and soils (and hence reductions in other types of ecosystem services). Policy applications for ecosystem accounts include both decision-making about land use options and trade-offs, as well as a tool for ongoing management of ecosystems. Greater synergy in the information system and policy development will enhance efforts to tackle problems of global change.

Carbon accounting in the SEEA is currently described in the following sections:

(i) SEEA EEA thematic account of carbon stocks and stock changes, but these are not integrated within the ecosystem asset and services accounts (Table 4.6).
(ii) SEEA EEA asset account can include indicators of ecosystem condition related to carbon, but the examples given are for carbon flows (Table 4.4).
(iii) SEEA EEA ecosystem service account includes the regulating service of carbon sequestration measured as an annual carbon flow (Table 3.1).
(iv) SEEA EEA carbon storage as a regulating service is stated as the avoided emissions from a carbon stock that is at risk of loss (Annex A3.13, A3.17).
(v) SEEA CF Natural inputs are physical flows from the environment used in production, which includes biomass in timber production. (It also shows oil and coal from the geosphere but this is not considered in this paper which is focused on the biosphere.)
(vi) SEEA CF Products include transfers of carbon stock through the production chain, such as wood and paper products.
(vii) SEEA CF Residuals are physical flows discarded by production to the environment, including air emissions of gross anthropogenic emissions of greenhouse gases.
(viii) CICES v5.1 (2.2.6.1) includes regulation of the concentration of atmospheric gases that impact global climate, with the example of carbon sequestration, where the benefit is climate regulation resulting in avoided damage costs.

Hence, there appears to be some inconsistency in how carbon stocks and flows are treated in the SEEA and separated components in ecosystem accounts and the central framework. In the revision of the SEEA EEA it is important to ensure the information system is strengthened to incorporate the benefits of all stocks and flows from ecosystems.

Components of current carbon accounting being used for international conventions supporting climate mitigation are listed in Table S2. These show some of the gaps and inconsistencies being applied currently.

### Enhancing current accounting approaches

Accounts of carbon stocks and flows provide information to identify options for mitigation activities, assess their relative benefits, and prioritise investments. However, current approaches to accounting need enhancing to achieve these purposes. For example, expanding the guidelines and combining the GHG inventories from the UNFCCC and proposals for the SEEA EEA revision. Table 1 describes some of the current conceptions related to accounting approaches, the potential for perverse outcomes, and the additions needed in an accounting system to ensure comprehensiveness to support a range of applications. Using the SEEA as an information system, which combines data from various sources, will encourage and facilitate consistency in policy development across international conventions. The information system is designed to be a comprehensive and mutually exclusive classification, objective in presentation of data, demonstrate links between ecosystems and their benefits to humans, and in a format relevant to inform policy.

**Table 1.** Summary of enhancements to the carbon accounting framework that address current conceptions, potential perverse outcomes and the additions needed for comprehensive accounting.

| Current conceptions | Potential perverse outcomes | Additions needed in accounting |
|---|---|---|
| 1. Active forest management is needed to sustain the strength of the carbon sink[1,2,3] | Primary forests are harvested to establish secondary forests or plantations. | • Carbon debt from initial harvesting.<br>• Timeframe for mitigation benefits (sequestration in the next decade is better than in the future). |
| 2. Emissions from forests are mainly due to deforestation where a change in land use occurs[4] | Emissions from harvesting and regrowing forests are not adequately accounted. | Measurement techniques are needed to estimate emissions from forest degradation (where land use of forestry does not change). |
| 3. Net annual ecosystem carbon balance is used as the metric for carbon sequestration. | • Carbon stocks in all reservoirs are counted equally without consideration of the longevity of the stock.<br>• Primary forests are harvested to establish secondary forests or plantations. | • Carbon stocks and flows are included in accounts<br>• Mitigation benefit includes longevity, calculated as an increase in the long-term average carbon stock of the ecosystem under a permanently changed land management system.<br>• Avoided loss of stocks is included as an ecosystem service. |
| 4. Flows of carbon are equivalent from all reservoirs. | Carbon stored in short-term reservoirs (eg plantations) is counted as an equal benefit as that in long-term stable reservoirs (eg primary forests). | Reservoirs of carbon classified by ecosystem types that reflect different qualities of carbon stocks and their risks of loss. |
| 5. Definition of 'forest' is based on tree height, cover and area of the potential land use. | Primary forests are harvested to establish secondary forests or plantations, and can include bare ground during a rotation. | Reservoirs of carbon classified by ecosystem types of actual land cover. |
| 6. Mitigation requires activities to reduce emissions or increase sequestration from a business-as-usual baseline. | Incentives are provided to countries that have degraded forest carbon stocks (or are planning to) and hence have the potential for sequestration, but are not provided to maintain and protect existing carbon stocks in natural ecosystems. | Carbon storage is included as an ecosystem service and classified by the quality of the reservoir. |
| 7. The reference level is the current carbon stock or temporal baseline. | Carbon sequestration potential cannot be assessed. | The reference level is the natural state so that the initial loss of carbon is accounted. |
| 8. Net carbon flows are reported. | Attribution of gross flows is not possible. | Gross carbon flows are reported, and additions and reductions attributed. |

[1]Nabuurs et al., 2007; [2]Canadell and Raupach, 2008; [3]Ciais et al., 2008; [4]IPCC AR5 2014

## Proposed carbon accounting framework

We present a comprehensive account of carbon stocks and flows in an ecosystem accounting framework that meets the standards required for accounting but also provides the information relevant to support policies for climate mitigation and ecosystem management (see Tables S3 and S4a,b). An integrated carbon account includes the relationships between asset tables, natural inputs, products, residuals and ecosystem services. The asset account for ecosystem condition consists of the stocks and stock changes of carbon and the flows between assets of the biosphere, oceans and atmosphere (Table S3). The ecosystem service is climate regulation (CICES 2016) and indicators include carbon sequestration (equal to the positive net annual carbon balance) and carbon storage (equal to the avoided carbon stock loss at risk) when either is attributed to 'additional human activities' (Figure 1).

In the context of climate change mitigation, sequestration represents the permanent transfer of carbon from the atmosphere to the biosphere; hence, quantification requires metrics of magnitude and longevity (Körner 2017). This time dimension is a critical addition to assessing benefits from ecosystems. Classifying ecosystem types by the quality of the reservoirs of carbon stocks provides an estimate of longevity (Table S3). Longevity refers to the average carbon stock of the ecosystem across the landscape and includes the effects of disturbance and regeneration.

Both carbon storage and sequestration are included in ecosystem accounts (Tables S4a,b) so that their distinct benefits are transparent. Regulating ecosystem services provide benefits derived from the existence as functioning ecosystems, both now and in the future. They do not necessarily have a current transaction value, but their integration with other ecosystem services within the ecosystem accounting framework is imperative to allow comparisons among services and analysis of trade-offs. Also shown in ecosystem flow accounts for carbon sequestration are the "negative benefits" from forest fires and emissions from harvesting (see Table S4a). The release of carbon from native forests types is shown as negative numbers in the supply account.

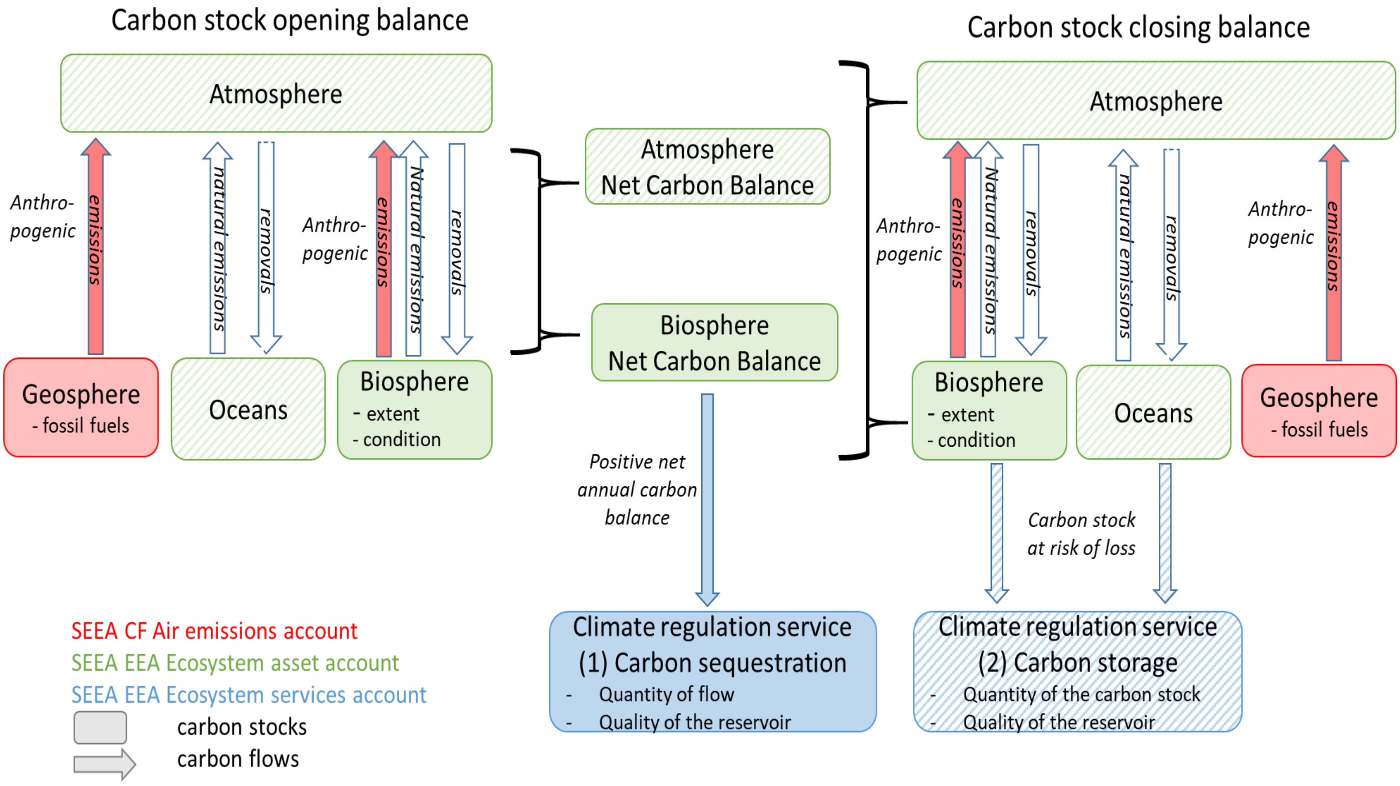


**Figure 1.** Carbon stocks and flows within the ecosystem accounting framework.
The ecosystem asset account consists of stocks in the biosphere in the SEEA EEA (green shaded), and should also include the oceans and atmosphere as assets (green hatched), geosphere and anthropogenic emissions (red shaded), and the gross flows between these assets (or reservoirs of carbon). The asset account consists of carbon stocks and stock changes over time from the opening balance to the closing balance. Stock change is calculated as the net ecosystem carbon balance, which represents a flow. The ecosystem service is climate regulation. Appropriate indicators, or measured variables, of climate regulation depend on the purpose of the accounts, the ecosystem types and management activities. Indicators of the ecosystem service include (1) carbon sequestration (blue shaded), equal to the positive net annual carbon balance that is attributed to 'additional human activities'; and should also include (2) carbon storage (blue hatched), equal to the avoided carbon stock loss at risk from 'additional human activities'.

Characteristics of the carbon accounting framework include:

1. **All land** is included in comprehensive accounts, irrespective of the degree of human management, so that there is no artificial distinction between managed and unmanaged lands, and hence net carbon stock change represents the total exchange between biosphere and atmosphere. All ecosystems provide benefits of carbon storage and this is recognised in the accounts. All land requires some form of management, for example conservation or protected lands require control of weeds and feral animals, fire management, possibly fencing, roads or public access and amenities. The accounts are spatially referenced so that gross flows and stocks can be attributed. This comprehensive coverage facilitates whole landscape solutions that integrates mitigation, adaptation and resource management.

**2. All carbon pools** are included in the account – above- and below-ground biomass, dead standing biomass, coarse woody debris, litter and soil carbon. Data availability and quality may vary for these different pools, but estimates of all pools should be included.

**3. Quality of carbon stocks,** in terms of their stability, capacity and time required for restoration, are differentiated by classification of ecosystem types as reservoirs of carbon. An appropriate classification of ecosystems is natural or primary, production in native ecosystems, and human-modified ecosystems such as plantations or agricultural areas (plantations should be classified as a tree crop) (FAO 2018) (SEEA EEA Annex A4.1). This classification within the accounting system facilitates tracking the transfers of carbon stocks between classes of increasing human impact and attributing additions and reductions in stock to natural or human factors. The classification provides a qualitative assessment of risk of loss of the carbon stock.

**4. The definition of 'forest'** as a land cover type should refer to the actual vegetation cover at the time of accounting, not the potential vegetation type which may include a temporary change. The definition used in GHG inventories allows countries to choose within the following ranges of parameters: minimum area of land of 0.05 – 1.0 ha, tree crown cover more than 10 – 30%, with tree height minimum of 2 – 5 m at maturity (IPCC 2003). At the lower end of this range, considerable loss of trees can occur without the activity being classified as deforestation. Changes in forest structure, carbon stocks and biodiversity should be included in the definition and classification of forests.

**5. The biosphere and atmosphere** are distinguished as separate spatial units in a three-dimensional delineation of the accounting system, for the context of carbon accounting, so that transfers are counted explicitly. Separate units allow complete accounting for flows of carbon (and other elements) between the biosphere and atmosphere, and flows between the atmosphere and the economy, including ascribing a carbon storage function to the atmosphere.

**6. A reference level** of the natural state of the ecosystem, which represents the carbon carrying capacity, is used to assess changes in carbon stocks. This includes the initial loss of carbon due to human activities, as well as historical changes. Additional comparisons may be required for specific policy purposes, such as scenarios using baseline years or the counterfactual of 'business-as-usual' land management activities to assess the impact of future changes in activities.

**7. Gross flows** are reported, not net flows, so that all sources of emissions and removals are transparent. Flows from all ecological processes should be included, or at least estimated: photosynthesis, autotrophic and heterotrophic respiration, and combustion. Gross flows show the growth potential and therefore carbon sequestration from natural forests and proforestation of secondary forests (Moomaw et al. 2019). This is hidden currently in the net analysis of emissions and removals from land use. Removals of carbon (sequestration) are treated separately from emissions reductions, so that sequestration is not seen as an offset. Reporting both emissions and removals that contribute to a net change in stock is important to understand the factors driving change, and hence where to make meaningful management interventions to increase stocks.

**8. Ecosystem condition** for carbon stocks is characterised by the carbon density or accumulation, net ecosystem carbon balance or rate of sequestration, longevity of the stock, stability and resilience related to risk of loss. These characteristics determine the capacity of ecosystems to produce the ecosystem service of climate regulation.

**9. Permanence** is included as a criteria in the accounting by measuring and reporting all carbon stocks and changes in stocks over time against a single reference level.

**10. Impacts of natural and anthropogenic disturbances** in changing carbon stocks are attributed in the asset accounts for additions and reductions in stock.

**11. The ecosystem service of climate regulation** is derived from the magnitude and longevity of the carbon stock in the biosphere, and the consequent stock in the atmosphere. The benefit of the carbon stock in the biosphere depends on the ecosystem condition or quality of the reservoir, which is interdependent with ecosystem integrity. Carbon storage, as a stock, is an ecosystem service that contributes to climate regulation.

Design of the framework for ecosystem accounting should encompass the best possible theoretical understanding of the system, even if there may be challenges in measuring all components. Current challenges include measuring total carbon stocks and stock changes in all components in the biosphere and accumulation in the economy, differentiating qualities of carbon stocks, and identifying proportions of carbon stocks in reservoirs at risk of loss. Comprehensiveness of the accounting framework is fundamental to allow all potential ecosystem services, with benefits now or in the future, to be identified and evaluated.

## Example of comprehensive carbon accounts

The carbon accounting framework is illustrated for a case study forest region in the Central Highlands of Victoria, Australia. It includes:

(1) physical supply and use table including the ecosystem services of carbon storage (stocks) and carbon sequestration (flows) (Table S4a);

(2) integrated carbon account including ecosystem services related to the qualities of reservoirs in the biosphere and atmosphere, natural inputs, products and carbon dioxide emissions (Table S4b).

The data presented in these tables are derived from an intensive study of carbon dynamics in a wet, temperate eucalypt forest. These data have been re-analysed for recording in ecosystem accounts for the purpose of demonstrating, in theory and practice, how both stocks and flows of carbon can be presented in a format useful for informing policy about benefits for climate mitigation and forest management.

The data sources included carbon stocks and annual stock changes in forest types: (i) conservation native forest, (ii) production native forest, (iii) hardwood plantation, (iv) softwood plantation, and (v) other land cover types within the Central Highlands study area for accounting (Keith et al. 2017a,b). These data are reported for ecosystem services in (i) forest available for harvesting, and (ii) forest areas not available for harvesting, as the management status of these forests is a key policy issue. The ecosystem services are (i) carbon sequestration as an annual stock change or flow, and (ii) carbon storage or the standing stock of carbon. These two ecosystem services are supplied by the environment based on a classification of land cover spatial units. The ecosystem services are used by economic units classified by industries. Carbon sequestration and storage in production forests available for harvesting are used by the forestry industry. Carbon sequestration and storage in conservation forests are a collective good, and hence are assigned as a use by government in the accounts.

An integrated supply and use account for carbon related stocks and flows is demonstrated in Table S4b. This table shows the ecosystem services from the Experimental Ecosystem Accounts (UN et al. 2014a) and natural inputs, products and emissions from the Central Framework (UN et al. 2014b). These accounts show the flow of carbon from the environment and used by economic units, and the flow of products and emissions through different industries within the economy. The flow of carbon is shown diagrammatically for native forests and plantations, where the accounting treatment differs because of the assumed location of the production boundary (Figure 2a, b).

For native forests, the harvested wood is treated as a natural input supplied by the environment and used by the economy in the forestry industry. Emissions from fires and harvesting in the production forest are supplied by the forestry industry, and emissions from fires in conservation forests are supplied by the government, and all emissions are used by the environment in the atmosphere. The forestry industry supplies sawlogs and pulplogs that are used by wood and paper product manufacturing. Manufacturing supplies sawn timber and paper products that are used by other industries, such as construction, and emissions during processing are supplied by manufacturing and used by the atmosphere. Other industries supply timber and paper products that are used by households. At the end-of-life of products, households supply waste that is used by waste management and emissions that are used by the atmosphere.

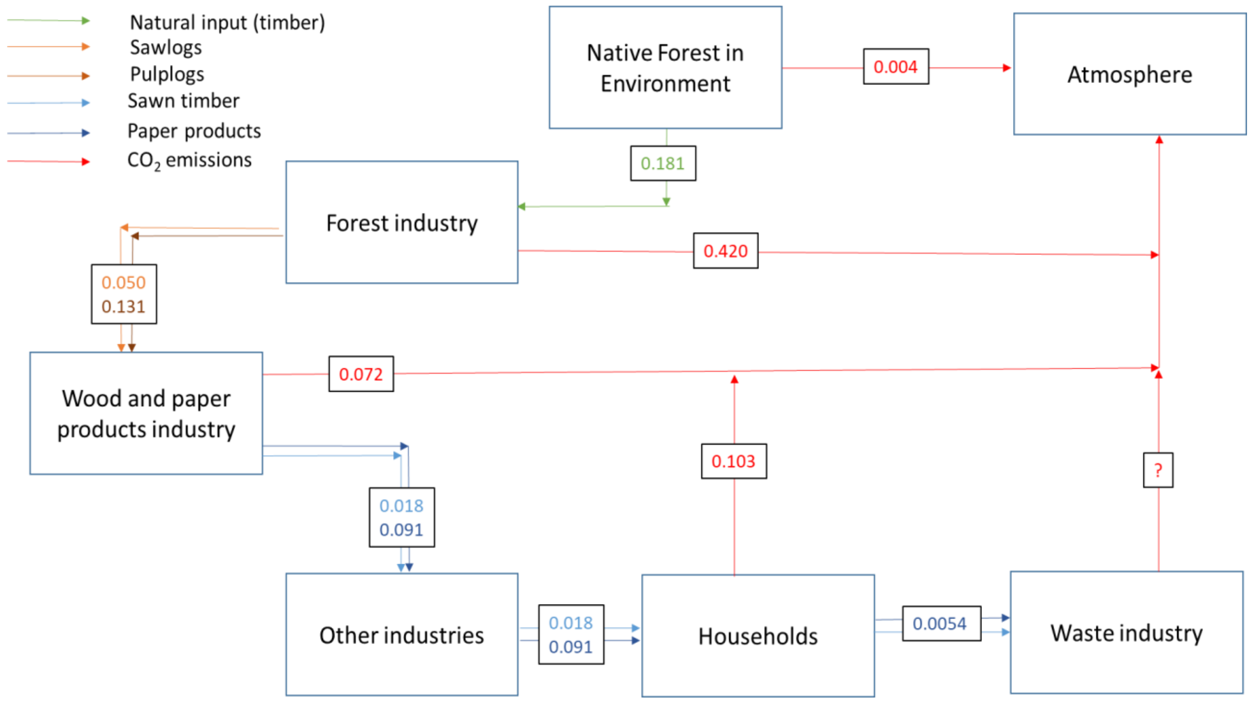


**Figure 2a**. Carbon flows (Mt C) in the native forest within the study region showing harvesting and transfer from the environment through natural inputs to the economy, and then transfers between products and emissions (data from the accounts in Table S4b).

For plantations, these are already within the economy according to the SEEA Central Framework and so annual biomass increment is the amount supplied by the forestry industry. The forest industry then supplies sawlogs and pulplogs shown by plantation type (hardwood or softwood). The use of products by wood and paper product manufacturing is the volume of sawlogs and pulplogs supplied to industries. Accumulation in an inventory is calculated as the difference between annual increments and the amount used by industry. A positive difference represents a supply in the inventory, whereas a negative difference represents a use of the inventory.

Examples of how the accounting rules may influence the results and their interpretation for management decisions are shown for the Central Highlands region (Table S5). Application of these results have been used to inform policies for climate change mitigation actions and regional forest management.

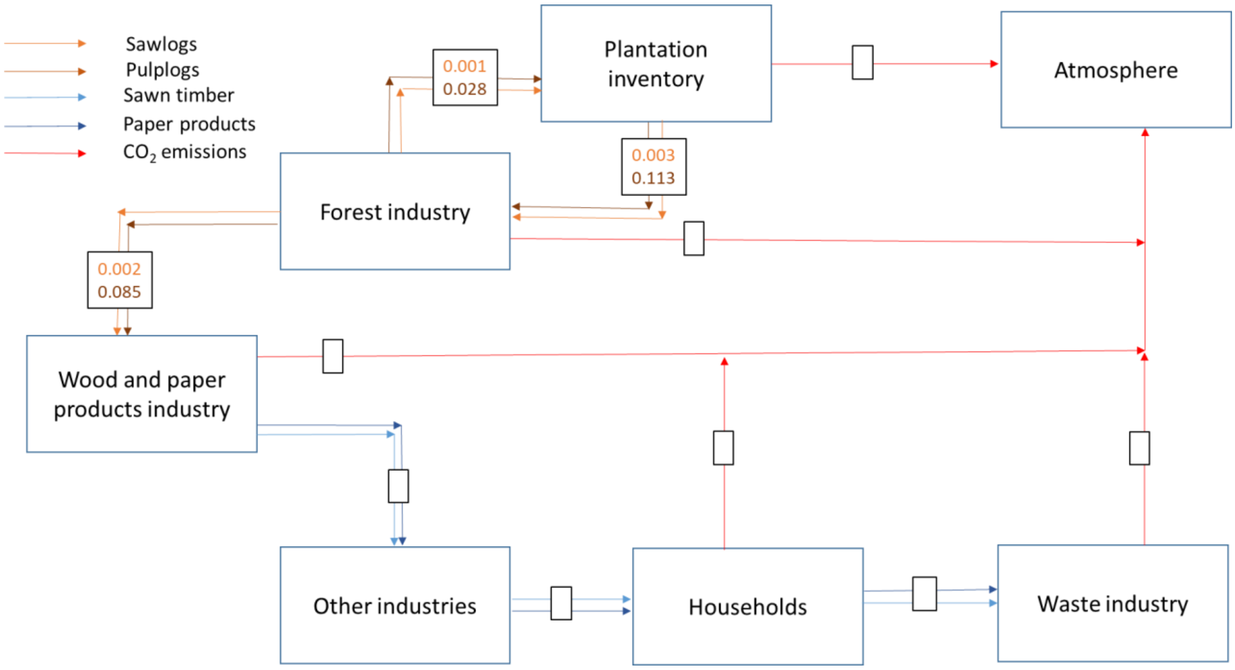


**Figure 2b**. Carbon flows (Mt C) in hardwood plantations within the study region, that is within the economy showing harvesting and transfer between products and emissions (data from the accounts in Table S4b).

## Role of carbon stocks and flows in mitigation

The importance of accounting for both stocks and flows is illustrated by the impact of changes in forest management with an example using the case study from wet, temperate eucalypt forest in south-eastern Australia (Figure 3). Measuring and reporting changes in carbon stocks over the long term is critical, as well as the annual flows. Carbon storage is represented by the long-term average carbon stock in an ecosystem at a landscape scale, irrespective of temporal variability in emissions and removals and spatial variability due to disturbance or climate variability. The average carbon stock of an ecosystem is determined by the environmental conditions, land use, and regime of natural and anthropogenic disturbances. Accounting periods for net carbon flows and assumed transition periods for changes in human activities of 20 years (IPCC 2006) do not include historic carbon losses (such as harvesting primary forest) and complete carbon dynamics (such as an 80 year logging rotation). Consequently, the full impact of changes in land use are not accounted and the carbon sequestration potential cannot be predicted.

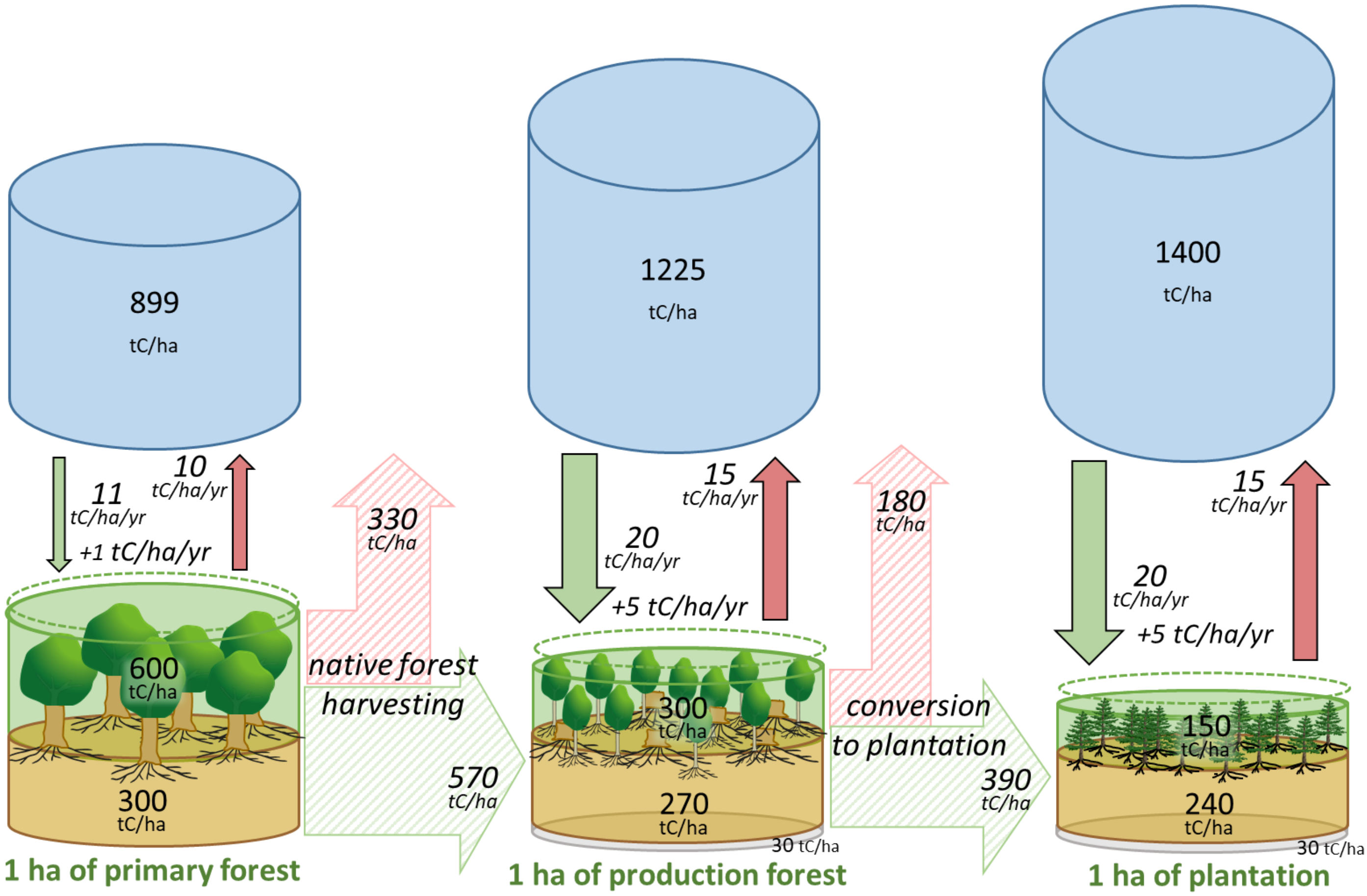


**Figure 3.** Carbon stocks (roman type) and flows (*italic type*) in a wet, temperate eucalypt forest in south-eastern Australia showing the changes due to forest management. Carbon stocks in all reservoirs (soil - brown, biomass - green, products and residuals – grey, atmosphere - blue) quantified as tC ha$^{-1}$, and assuming transfer between reservoirs within a vertical cylinder. Conversion of a primary forest to a secondary production forest and then a plantation results in a reduction in carbon stock in the biosphere and increase in carbon stock in the atmosphere, even though the annual net flow (tC ha$^{-1}$ yr$^{-1}$ with photosynthesis shown as green arrows and respiration shown as red arrows) shows a higher rate of carbon sequestration in the production forest and plantation (5 tC ha$^{-1}$ yr$^{-1}$) than in the primary forest (1 tC ha$^{-1}$ yr$^{-1}$). Emissions due to conversion of forest management types (red hatched arrows) with native forest to production forest (330 tC ha$^{-1}$), and production forest to plantation (180 tC ha$^{-1}$), have sometimes not been included in accounts if they occurred before the recording period. Hence, the carbon sequestration potential is not known. Values are derived from studies in wet, temperate eucalypt forest: Keith et al. (2009), Rab (1994), Keith et al. (2014), Ajani and Comisari (2014).

## Valuation methods for carbon storage and sequestration

Carbon storage and carbon sequestration represent different components of the carbon cycle and so require different methods of valuation, with a range of options (Table 2). Sequestration refers to marginal quantity changes. The first distinction in concepts of valuation is between the polluter pays or the beneficiary pays, which will have different policy solutions. The social cost of carbon is the net economic damage caused by emissions of additional carbon in the future, however this is difficult to determine because of many interacting and complex factors. The cost of avoiding carbon stock losses by maintaining stable stocks in the biosphere and preventing emissions to the atmosphere can be determined more easily, but often underestimates the true social cost.

**Table 2.** Options for valuation of carbon storage and sequestration

| | |
|---|---|
| **Valuation for carbon storage** | |
| Land value | • Market value is function of the value of a combination of ecosystem asset condition indicators e.g. carbon storage, water, tourism |
| | • Market value for an alternate land use |
| Avoided carbon stock loss | • Replacement cost of the carbon that was lost and would need to be stored in another form in the biosphere. Equivalent to a notional rent or payment avoided by having the asset. |
| | • Benefit calculated each year in the Profit and Loss Account. The value depends on the risk of the investment in carbon storage (analogous to investment in a secure bank) |
| | • Abatement cost estimate based on a supply curve of cost of avoiding the carbon emissions |
| | • Discounted flow of all future benefits and calculation of Net Present Value |
| | • Market value e.g. REDD+, voluntary markets |
| Management cost | • Cost of production to manage the land for carbon storage, e.g. National Park |
| Avoided damage cost | • Based on a demand curve of damages avoided by storing carbon in the biosphere, equivalent to the social cost of carbon. |
| Fixed asset | • Value of a fixed asset on the Balance Sheet |
| Appreciating asset | • The value of storage increases each year because the impact of emissions increases as climate change worsens and the cost of damage rises, and value depends on the quality of the carbon stocks |
| Notional rent | • Rental worth or payment avoided by having the fixed asset of carbon storage |
| Insurance | • Payment to protect stable carbon stocks in primary forests from the risk of loss may be considered like payments for life insurance that provides some security for future generations. |
| Qualitative rating | • Rating of carbon stocks based on their risk of loss from the quality of the reservoirs of natural, semi-natural and plantation ecosystems, rated as high – medium – low. |
| Warehousing | • Maintaining a stock of carbon related to the quality of the reservoir.<br>• Possible valuation method using replacement value of a different reservoir of comparable quality. |
| Stockpiling | • Inventory of accumulation |
| Ecological Fiscal Transfer | • Area of forest cover in the recent past used as an indicator of carbon storage, combined with other ecosystem services, in a multi-element formula that determines the distribution of tax revenue to states as a payment for performance (Busch 2019) |
| **Valuation of carbon sequestration** | |
| Income | • Future expected income from carbon sequestration |
| Market price | • Market price from emissions trading schemes |
| **Valuation for alternate land uses** | |
| Timber production | • Value of the forest for future wood production, calculated as a Net Present Value (discounted future income of the products) |

## Conclusions

Designing the best possible framework for carbon accounting is imperative. This is to ensure policies for mitigation are prioritising the most effective activities, and the outcomes from activities succeed in increasing carbon storage in the biosphere and reducing the carbon concentration in the atmosphere. An accounting framework that includes all reservoirs, and their carbon stocks and flows, allows selection of the most appropriate accounts to be developed for different purposes to enhance policy options for climate change mitigation.

Accounting for carbon stocks and flows in the land sector has the highest uncertainty of all sectors shown in the IPCC accounting (Friedlingstein et al. 2014), yet countries are expecting high mitigation contributions from land use, especially forests, in their Nationally Determined Contributions (NDCs) (Grassi et al. 2017, Rockström et al. 2017). Reducing the level of uncertainty in measurement and improving transparency in reporting are key objectives for accounting systems and ensuring the links between land use activities, mitigation outcomes and tracking towards global goals. This comprehensive information can be used to assess trade-offs between land uses for maximising carbon storage and food production, for example, by determining the carbon storage opportunity cost of land conversion (Searchinger et al. 2018).

A comprehensive accounting system that links carbon stocks and flows with other ecosystem assets and services, and benefits to humans, will provide consistent information for international conventions. Conventions that are being negotiated in the near future include the Paris Rulebook and revised NDCs, IPCC 6th Assessment Report, the Sustainable Development Goals and the Convention on Biological Diversity with new targets being set in 2020. Within the same timeframe, the SEEA EEA revision process aims to achieve a statistical standard by 2020. Developing synergies, identifying interdependencies, and coordinating activities in the development of rules, protocols and targets will strengthen all these conventions.

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## Supplementary Information

### Table S1

International environmental instruments and their use of information from carbon accounts.

| Policy framework | Policy goal | Data needs |
|---|---|---|
| **UNFCCC**<br>Kyoto Protocol<br>Paris Agreement<br>REDD+ | • Maintain the stock of $CO_2$ in the atmosphere below 450 ppm | • Carbon stocks and change in stocks, by activity, land unit, country |
| **OECD Green Growth Indicators**<br>demand-based indicators of carbon productivity | • Decoupling carbon emissions from economic growth | • Combined economic and environmental data<br>• Change in natural assets (carbon stocks) |
| **Sustainable Development Goals**<br>13. Action on Climate Change<br>15. Sustainable use of terrestrial ecosystems | • National policies to achieve low GHG emissions development<br>• Foster resilience to climate change impacts<br>• Define and demonstrate sustainable use of ecosystems | • Combined economic, carbon stock and flow data<br>• Factors and interactions contributing to ecosystem resilience<br>• Monitor all ecosystem services and change over time |
| **Convention on Biological Diversity**<br>Aichi Targets<br>IPBES Intergovernmental Science Policy Platform of Biodiversity and Ecosystem Services | • Safeguard ecological limits<br>• Sustainable production and consumption<br>• Reduce habitat loss<br>• Sustainable land management in terms of supply of ecosystem services<br>• Restoration of degraded ecosystems | • Ecosystem services of carbon storage and sequestration defined by ecosystem and management types, and interactions with other ecosystem services<br>• Includes only reforestation and afforestation projects |
| **Natural Capital Protocol**<br>(coalition of > 300 organisations) | • Enable organisations to identify, measure and value direct and indirect impacts and dependencies on natural capital<br>• Benefits for business, communities and economy | • Co-benefits for ecosystems of management for adaptation and mitigation |

Table S2

Components of carbon accounting currently being used in international conventions

| Instrument | Components of carbon included | Quality of carbon stocks included | Land areas included | Disturbance included | Measurements used | Reporting requirement | Goals | Potential problems |
|---|---|---|---|---|---|---|---|---|
| Kyoto Protocol | Anthropogenic net annual emissions against a (variable) reference year | No differentiation of forest types | Managed land only | Natural disturbance included in the reference level | National GHG inventory of anthropogenic emissions and removals. Mitigation activities need to create change for 20 years (IPCC 2006) | IPCC guidelines (2006) on accounting principles and methodologies | National Kyoto commitments | Human activity impacts all lands but to varying extents |
| Paris Agreement | Includes the criteria of maintaining ecosystem integrity | | | | National GHG inventory of anthropogenic emissions and removals | Kyoto rules. 2019 refinement of IPCC guidelines | Nationally Determined Contributions | Accounting methods in the land sector, comprehensiveness and uniformity across countries are unclear, may be limited to fluxes related to planned mitigation activities |
| Katowice Climate Change Package | Includes reference year(s), reference indicator of emissions reduction | | | | Nationally decided accounting methods to determine NDCs. | Global Stocktake every 5 years. National accounting based on IPCC | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Liabilities for mitigation activities should be included under national accounting (Federici et al. 2017). | guidelines (2019) | | |
| REDD+ | Reducing emissions, and conservation and enhancement of carbon stocks. The objective creates financial value for carbon stored in forests, with incentives to avoid carbon stock loss (UNFCCC COP 7 Bali, Wilder et al. 2014) | No differentiation of forest types | National / subnational reporting by developing countries with project areas in forests | | Change in average carbon stock over the accounting period [1] Retrospective performance-based payments[2] Estimating difference in emissions under changed management (UNFCCC COP 19 Warsaw). | REDD guidelines | Emissions reduction against a reference level of emissions as business-as-usual. | Projects concentrating on reducing emissions in areas of immediate risk. Reporting on forest emissions and removals may not be comprehensive, eg omitting degradation. Reference levels based on emissions over a period. Initial average carbon stock may not be the natural state. |

[1] Global Forest Observation Initiative 2016. Methods and Guidance Documentation. http://www.fao.org/gfoi/components/methods-and-guidance-documentation/en/

[2] FAO 2017. Forests and Climate Change Working Paper 15. From reference levels to results reporting: REDD+ under the UNFCCC. http://www.fao.org/3/a-i7163e.pdf
Wilder M, Millar I, Dibley A, Wilson K et al. 2014. The consolidated guide to the REDD+ rules under the UNFCCC. Report by Baker & McKenzie Law for Development Initiative. p 98. http://www.bakermckenzie.com/reddrulebook

Table S3.

Comprehensive carbon accounting table showing stocks, stock changes and resulting flows. The terrestrial biocarbon section has been expanded to show a land cover classification that denotes differences in the qualities of the reservoirs in terms of the longevity and risk of loss of carbon stocks. Transfers of carbon between these classes, recorded as additions and reductions, will make these changes in the quality of the stock transparent. Current accounting systems include biocarbon stocks in semi-natural ecosystems, plantations, agriculture, geocarbon and accumulations in the economy. Biocarbon in natural ecosystems, aquatic and marine ecosystems are not included in the economy in current accounting systems. The carbon stock and gross flows in the atmosphere are not included, but emissions from fossil fuels and managed lands are included.

| | Outside the economy | | | | | | | | Accounted within the economy | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Atmosphere | Oceans | Biocarbon | | | | | | | | | | | | | | | Geocarbon | Accumulation in the economy |
| | | | Aquatic | Marine | Terrestrial | | | | | | | | | | | | | | |
| | | | | | Natural ecosystems | | | | Semi-natural ecosystems | | | | Plantations | | | Agriculture | | | |
| | | | | | Rainforest | Forest | Woodland | Peatlands | Selectively logged rainforest | Regrowth forest | Grazed woodland | Drained peatland | Softwood sawlog | Hardwood sawlog | S/H wood pulplogs | Annual | Perennial | | |
| **Opening stock of carbon (C $t_0$)** | | | | | | | | | | | | | | | | | | | |
| **Additions to stock** | | | | | | | | | | | | | | | | | | | |
| Natural expansion | | | | | | | | | | | | | | | | | | | |
| Managed expansion | | | | | | | | | | | | | | | | | | | |
| Discoveries | | | | | | | | | | | | | | | | | | | |
| Upward reappraisals | | | | | | | | | | | | | | | | | | | |
| Reclassifications | | | | | | | | | | | | | | | | | | | |
| Total additions to stock | | | | | | | | | | | | | | | | | | | |
| **Reductions in stock** | | | | | | | | | | | | | | | | | | | |
| Natural contraction | | | | | | | | | | | | | | | | | | | |
| Managed contraction | | | | | | | | | | | | | | | | | | | |
| Downward reappraisals | | | | | | | | | | | | | | | | | | | |
| Reclassifications | | | | | | | | | | | | | | | | | | | |
| Total reductions in stocks | | | | | | | | | | | | | | | | | | | |
| **Imports and exports** | | | | | | | | | | | | | | | | | | | |
| Imports | | | | | | | | | | | | | | | | | | | |
| Exports | | | | | | | | | | | | | | | | | | | |
| **Closing stock of carbon (C $t_1$)** | | | | | | | | | | | | | | | | | | | |
| **Net ecosystem carbon balance (C $t_1$ - C $t_0$)** | | | | | | | | | | | | | | | | | | | |

Table S4a.

Supply and use of carbon sequestration and carbon storage.

| PHYSICAL SUPPLY | Economic Unit | | | | | | | | | Environment Unit | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Biosphere | | | | | | | | | |
| | Agriculture, Forestry & Fisheries | Wood & paper product manufacturing | Waste management | Energy | Other Industries (eg construction) | Government* | Households | Inventory | Imports | Artificial Surfaces | Crops and horticulture | Plantation forest - hardwood | Plantation forest - softwood | Natural forest | Other vegetation | Grassland | Total biosphere | Atmosphere | TOTAL SUPPLY |
| **Ecosystem Services** | | | | | | | | | | | | | | | | | | | |
| Carbon sequestration | | | | | | | | | | | | | | | | | | | |
| *- forest harvested* | | | | | | | | | | | | *0.115* | *0.008* | *0.216* | | | *0.339* | | *0.339* |
| ** removals due to growth* | | | | | | | | | | | | | | *0.632* | | | | | |
| ** emissions due to fire* | | | | | | | | | | | | | | *-0.002* | | | | | |
| ** emissions due to harvesting* | | | | | | | | | | | | | | *-0.414* | | | | | |
| *- forest not harvested* | | | | | | | | | | | | | | *1.360* | | | *1.360* | | *1.360* |
| ** removals due to growth* | | | | | | | | | | | | | | *1.368* | | | | | |
| ** emissions due to fire* | | | | | | | | | | | | | | *-0.008* | | | | | |
| ** emissions due to harvesting* | | | | | | | | | | | | | | *0.000* | | | | | |
| *- all other biosphere* | | | | | | | | | | *0.001* | *0.000* | | | | *0.000* | *0.000* | *0.001* | | *0.001* |
| **Total biosphere carbon sequestration** | | | | | | | | | | 0.001 | 0.000 | 0.115 | 0.008 | 1.576 | 0.000 | 0.000 | 1.700 | | 1.700 |
| Sub-total non-biosphere carbon sequestration | | | | | | | | | | | | | | | | | | | |
| **Total carbon sequestration** | | | | | | | | | | 0.001 | 0.000 | 0.115 | 0.008 | 1.576 | 0.000 | 0.000 | 1.700 | | **1.700** |
| Carbon storage | | | | | | | | | | | | | | | | | | | |
| *- forest harvested* | | | | | | | | | | | | *4.258* | *0.577* | *30.210* | | | *35.045* | | *35.045* |
| *- forest not harvested* | | | | | | | | | | | | | | *111.570* | | | *111.570* | | *111.570* |
| *- all other biosphere* | | | | | | | | | | *0.253* | *0.037* | | | | *0.322* | *0.211* | *0.823* | | *0.823* |
| Sub-total biosphere carbon storage | | | | | | | | | | 0.253 | 0.037 | 4.258 | 0.577 | 141.780 | 0.322 | 0.211 | 147.438 | | 147.438 |
| Sub-total non-biosphere carbon storage | | | | | | | | | | | | | | | | | | | |
| **Total carbon storage** | | | | | | | | | | 0.253 | 0.037 | 4.258 | 0.577 | 141.780 | 0.322 | 0.211 | 147.438 | | **147.438** |

| PHYSICAL USE | Economic Unit | | | | | | | | | Environment Unit | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Biosphere | | | | | | | | | |
| | Agriculture, Forestry & Fisheries | Wood & paper product manufacturing | Waste management | Energy | Other Industries (eg construction) | Government* | Households | Inventory | Imports | Artificial Surfaces | Crops | Plantation forest - hardwood | Plantation forest - softwood | Natural forest | Other vegetation | Grasslands | Total biosphere | Atmosphere | TOTAL USE |
| **Ecosystem Services** | | | | | | | | | | | | | | | | | | | |
| Carbon sequestration | | | | | | | | | | | | | | | | | | | |
| *- forest harvested* | *0.339* | | | | | | | | | | | | | | | | | | *0.339* |
| ** native forest* | *0.216* | | | | | | | | | | | | | | | | | | |
| ** plantations* | *0.123* | | | | | | | | | | | | | | | | | | |
| *- forest not harvested* | | | | | | *1.360* | | | | | | | | | | | | | *1.360* |
| *- all other biosphere* | | | | | | *0.001* | | | | | | | | | | | | | *0.001* |
| Sub-total biosphere carbon sequestration | 0.339 | | | | | 1.361 | | | | | | | | | | | | | 1.700 |
| Sub-total non-biosphere carbon sequestration | | | | | | | | | | | | | | | | | | | |
| **Total carbon sequestration** | 0.339 | | | | | 1.361 | | | | | | | | | | | | | **1.700** |
| Carbon storage | | | | | | | | | | | | | | | | | | | |
| *- forest harvested* | *35.05* | | | | | | | | | | | | | | | | | | *35.045* |
| ** native forest* | *30.21* | | | | | | | | | | | | | | | | | | |
| ** plantations* | *4.84* | | | | | | | | | | | | | | | | | | |
| *- forest not harvested* | | | | | | *111.57* | | | | | | | | | | | | | *111.570* |
| *- all other biosphere* | | | | | | *0.82* | | | | | | | | | | | | | *0.823* |
| Sub-total biosphere carbon storage | 35.05 | | | | | 112.39 | | | | | | | | | | | | | 147.438 |
| Sub-total non-biosphere carbon storage | | | | | | | | | | | | | | | | | | | 147.438 |
| **Total carbon storage** | 35.05 | | | | | 112.39 | | | | | | | | | | | | | **147.438** |

*Use of carbon sequestration and carbon storage is shown by government as this is the SNA convention for showing collective uses.

Table S4b.

Combined presentation of ecosystem services of carbon sequestration and carbon storage, natural inputs, products and carbon dioxide emissions.

| PHYSICAL SUPPLY | Economic Unit | | | | | | | | | Environment Unit | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Biosphere | | | | | | | | | |
| | Agriculture, Forestry & Fisheries | Wood & paper product manufacturing | Other Industries (eg construction) | Households | Waste management | Energy | Government* | Inventory | Imports | Artificial Surfaces | Crops and horticulture | Plantation forest - hardwood | Plantation forest - softwood | Natural forest | Other vegetation | Grassland | Total biosphere | Atmosphere | TOTAL SUPPLY |
| **Ecosystem Services** | | | | | | | | | | | | | | | | | | | |
| Carbon sequestration | | | | | | | | | | | | | | | | | | | |
| *- forest available for harvest* | | | | | | | | | | | | *0.115* | *0.008* | *0.216* | | | *0.339* | | *0.339* |
| *- forest not available for harvest* | | | | | | | | | | | | | | *1.360* | | | *1.360* | | *1.360* |
| *- all other biosphere* | | | | | | | | | | *0.001* | *0.000* | | | | *0.000* | *0.000* | *0.001* | | *0.001* |
| **Total biosphere carbon sequestration** | | | | | | | | | | 0.001 | 0.000 | 0.115 | 0.008 | 1.576 | 0.000 | 0.000 | 1.700 | | **1.700** |
| **Atmosphere carbon sequestration** | | | | | | | | | | | | | | | | | | **0.420** | |
| Carbon storage | | | | | | | | | | | | | | | | | | | |
| *- forest available for harvest* | | | | | | | | | | | | *4.258* | *0.577* | *30.210* | | | *35.045* | | *35.045* |
| *- forest not available for harvest* | | | | | | | | | | | | | | *111.570* | | | *111.570* | | *111.570* |
| *- all other biosphere* | | | | | | | | | | *0.253* | *0.037* | | | | *0.322* | *0.211* | *0.823* | | *0.823* |
| **Total biosphere carbon storage** | | | | | | | | | | 0.253 | 0.037 | 4.258 | 0.577 | 141.780 | 0.322 | 0.211 | 147.438 | | **147.438** |
| **Atmosphere carbon storage** | | | | | | | | | | | | | | | | | | | |
| **Natural inputs** | | | | | | | | | | | | | | | | | | | |
| Timber - native forest | | | | | | | | | | | | | | 0.181 | | | 0.181 | | 0.181 |
| **Products** | | | | | | | | | | | | | | | | | | | |
| Sawlogs | | | | | | | | | | | | | | | | | | | |
| *- native forest* | *0.050* | *0.018* | *0.018* | *0.005* | | | | | | | | | | | | | | | *0.091* |
| *- plantation* | | | | | | | | | | | | | | | | | | | |
| ** hardwood* | *0.002* | | | | | | | *0.001* | | | | | | | | | | | *0.003* |
| ** softwood* | *0.005* | | | | | | | | | | | | | | | | | | *0.005* |
| Total Logs | 0.058 | | | | | | | | | | | | | | | | | | 0.058 |
| Pulp | | | | | | | | | | | | | | | | | | | |
| *- native forest* | *0.131* | *0.091* | *0.091* | | | | | | | | | | | | | | | | *0.313* |
| *- plantation* | | | | | | | | | | | | | | | | | | | |
| ** hardwood* | *0.113* | | | | | | | *0.027* | | | | | | | | | | | *0.140* |
| ** softwood* | *0.003* | | | | | | | | | | | | | | | | | | *0.003* |
| Total Pulp | 0.247 | | | | | | | | | | | | | | | | | | 0.247 |
| **Total Products** | **0.304** | **0.109** | **0.109** | **0.005** | | | | **0.028** | | | | | | | | | | | **0.555** |
| **Emissions** | | | | | | | | | | | | | | | | | | | |
| Production forest | | | | | | | | | | | | | | | | | | | |
| *- from fire* | *0.006* | | | | | | | | | | | | | | | | | | *0.006* |
| *- from harvesting* | *0.414* | | | | | | | | | | | | | | | | | | *0.414* |
| *- from processing* | | *0.072* | | *0.103* | | | | | | | | | | | | | | | *0.176* |
| Conservation forest | | | | | | | | | | | | | | | | | | | |
| *- from fire* | | | | | | | *0.004* | | | | | | | | | | | | *0.004* |
| **Total $CO_2$ emissions** | **0.420** | **0.072** | | **0.103** | | | **0.004** | | | | | | | | | | | | **0.600** |

| PHYSICAL USE | Economic Unit | | | | | | | | | Environment Unit | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Biosphere | | | | | | | | | |
| | Agriculture, Forestry & Fisheries | Wood & paper product manufacturing | Other Industries (eg construction) | Households | Waste management | Energy | Government* | Inventory | Imports | Artificial Surfaces | Crops | Plantation forest - hardwood | Plantation forest - softwood | Natural forest | Other vegetation | Grasslands | Total biosphere | Atmosphere | TOTAL USE |
| **Ecosystem Services** | | | | | | | | | | | | | | | | | | | |
| Carbon sequestration | | | | | | | | | | | | | | | | | | | |
| *- forest available for harvest* | *0.339* | | | | | | | | | | | | | | | | | | *0.339* |
| *- forest not available for harvest* | | | | | | | *1.360* | | | | | | | | | | | | *1.360* |
| *- all other biosphere* | | | | | | | *0.001* | | | | | | | | | | | | *0.001* |
| **Total biosphere carbon sequestration** | 0.339 | | | | | | 1.361 | | | | | | | | | | | | **1.700** |
| **Atmosphere carbon sequestration** | | | | | | | | | | | | | | | | | | | |
| Carbon storage | | | | | | | | | | | | | | | | | | | |
| *- forest available for harvest* | *35.045* | | | | | | | | | | | | | | | | | | *35.045* |
| *- forest not available for harvest* | | | | | | | *111.570* | | | | | | | | | | | | *111.570* |
| *- all other biosphere* | | | | | | | *0.823* | | | | | | | | | | | | *0.823* |
| **Total biosphere carbon storage** | 35.045 | | | | | | 112.393 | | | | | | | | | | | | **147.438** |
| **Atmosphere carbon storage** | | | | | | | | | | | | | | | | | | | |
| **Natural inputs** | | | | | | | | | | | | | | | | | | | |
| Timber - native forest | 0.181 | | | | | | | | | | | | | | | | | | 0.181 |
| **Products** | | | | | | | | | | | | | | | | | | | |
| Sawlogs | | | | | | | | | | | | | | | | | | | |
| *- native forest* | | *0.050* | *0.018* | *0.018* | *0.005* | | | | | | | | | | | | | | *0.092* |
| *- plantation* | | | | | | | | | | | | | | | | | | | |
| ** hardwood* | | *0.002* | | | | | | | | | | | | | | | | | *0.002* |
| ** softwood* | | *0.031* | | | | | | *0.026* | | | | | | | | | | | *0.056* |
| Total Logs | | 0.082 | | | | | | | | | | | | | | | | | 0.082 |
| Pulp | | | | | | | | | | | | | | | | | | | |
| *- native forest* | | *0.131* | *0.091* | *0.091* | | | | | | | | | | | | | | | *0.312* |
| *- plantation* | | | | | | | | | | | | | | | | | | | |
| ** hardwood* | | *0.085* | | | | | | | | | | | | | | | | | *0.085* |
| ** softwood* | | *0.017* | | | | | | *0.014* | | | | | | | | | | | *0.032* |
| Total Pulp | | 0.233 | | | | | | | | | | | | | | | | | 0.233 |
| **Total Products** | | **0.316** | **0.109** | **0.109** | **0.005** | | | **0.040** | | | | | | | | | | | **0.578** |
| **Emissions** | | | | | | | | | | | | | | | | | | | |
| Total $CO_2$ emissions | | | | | | | | | | | | | | | | | | 0.600 | **0.600** |

Table S5.

New insights revealed by comprehensive carbon accounts, showing the proposed new component of the carbon account, the information revealed and the potential for missing information.

| Information revealed by comprehensive accounting | Missing information from current accounting | Case study example |
|---|---|---|
| 1. All land included in spatial areas of ecosystem accounts | | |
| Managed (or production) forest and unmanaged (conservation) forest are included. ⇒ Comprehensive spatial area. | Some lands are excluded. Degree of management of land is difficult to distinguish. ⇒ Missing areas of land, confusion over definitions | More than half the carbon stock in the case study region is stored in conservation forests. |
| 2. All carbon pools | | |
| All carbon pools are recorded, even if estimated. ⇒ Comprehensive carbon stocks | Total change in carbon stocks may not be recognised if all pools are not measured. ⇒ Missing carbon stocks | Aboveground biomass is often reported, but 20% of tree biomass can be belowground, and 10-30% of total biomass is dead as standing trees, logs and litter. |
| 3. Quality of carbon stocks | | |
| Forest types distinguished as natural, production and plantation, which determine quality of the reservoir. ⇒ Risk of carbon loss can be assessed. | Carbon stocks in all forests are counted equivalent. ⇒ True mitigation value cannot be assessed. | Carbon stocks in dense, even-aged regrowth forests and plantations have a greater risk damage and carbon stock loss due to wildfire, pests and drought. |
| 4. Definition of forest | | |
| Carbon stocks and stock changes recorded for all land cover classes at the current time. ⇒ Actual changes are recorded | If a land cover class can be actual or potential, then changes may not be recorded. ⇒ Missing changes in carbon stocks | Harvested areas that do not regenerate are not counted as a loss in forest cover, and so the loss of carbon stock is not recorded. |
| 5. Biosphere and atmosphere | | |
| The biosphere and atmosphere recorded as separate environment units. ⇒ Transfers are transparent | All transfers to the atmosphere may not be recorded. ⇒ Total increase in atmospheric carbon stock underestimated | Emissions from activities in the biosphere are recorded as used by the atmosphere. |
| 6. Reference level of the natural state | | |
| Carbon stock change is calculated from the original condition of the ecosystem, or estimated as possible. ⇒ Defines carbon carrying capacity | Change since business-as-usual or mature forest at end of rotation does not account for initial stock loss. ⇒ Full carbon sequestration potential not realised | Old growth forest has at least 30% higher carbon stock than a mature production forest. |
| 7. Measuring and recording gross flows | | |
| Gross flows recorded as removals due to growth, emissions due to fire, and emissions due to harvesting ⇒ Shows absolute gains and losses | Net flows recorded<br>Net ecosystem carbon balance measured ⇒ Hides differences due to forest management | Higher rate of sequestration in conservation forest (2.42 tC $ha^{-1}$ $yr^{-1}$) than production forest (-0.56 tC $ha^{-1}$ $yr^{-1}$). |

| | | |
|---|---|---|
| 8. Ecosystem condition | | |
| Long-term average carbon stock is the metric assessed under different forest management regimes.<br>⇒ Shows difference in stock between biosphere and atmosphere | Sequestration in terms of annual biomass increment is used as the metric.<br>⇒ Longevity of the carbon stock is not accounted. | Long-term carbon storage in conservation forests is twice that stored in production forests, and hence has a greater mitigation benefit. |
| 9. Carbon storage as an ecosystem service | | |
| Carbon storage supplied by forests in the environment Use by government in the economy for collective good.<br>⇒ Shows mitigation benefit | If carbon storage is not supplied by the environment, then stock loss would be used by the atmosphere.<br>⇒ Hides risk of climate degradation | Loss of carbon stock in Central Highlands forest (147 Mt C) is equivalent to Australia's total emissions for 1 year. |
| 10. Opportunity cost if all forest continued growing. | | |
| Carbon sequestration potential is calculated as the difference between the current carbon stock and the carbon carrying capacity.<br>⇒ Shows the opportunity cost of protecting forests | Carbon sequestration potential cannot be calculated fully without a reference level of the natural state.<br>⇒ Sequestration potential not recognised | Continued regrowth of harvested forests has a carbon sequestration potential of 3 $tC\ ha^{-1}\ yr^{-1}$. |