Integrating and scaling data to create ecosystem accounts relevant to management decisions

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Heather Keith[1], Michael Vardon, David Lindenmayer and Emma Burns

Fenner School of Environment and Society
Australian National University

[1]Author for correspondence: <heather.keith@anu.edu.au>

Abstract

Application of ecosystem accounts for informing natural resource management policy requires extending information about ecosystem asset extent and condition, to incorporate change over time in relation to a reference state. This allows levels of degradation and restoration of ecosystems to be quantified, and hence indentify trade-offs between different land use activities. Understanding the drivers of these changes is critical for assessing the consequences of alternative activities. Concepts of condition will be most effective when indicators are designed to meet specific policy questions, and applied to specific components of ecosystem assets and services. We suggest differentiating the concepts and terminology for condition of an ecosystem asset relative to a reference state, compared with condition as the supply of ecosystem services.

Implementing the ecosystem accounting framework by scaling up site level data in a regional study in the Central Highlands of Victoria, Australia, has demonstrated technical and conceptual issues, and we provide examples of solutions from the carbon, water and biodiversity accounts. Based on this experience, we comment upon some of the topics in the SEEA EEA research agenda and the SEEA EEA Technical Recommendations Consultation Draft March 2017 concerning definitions and implementation of concepts of ecosystem condition and how these are applied to thematic accounts.

Ecosystem accounts were developed using a metric of condition in relation to a reference state. The condition metric of forest age was determined by time since stand-replacing disturbance events and related to a reference state of old growth forest. Carbon accounts were developed from biomass carbon stock density modelled spatially across the landscape and calibrated with site data of merasurements of biomass components. Change over time in carbon stocks was determined from ecological production functions that described processes of carbon gain and loss from the ecosystem and in relation to distbance events. The water asset account included the water stored in reservoirs, with the ecosystem service of water provisioning defined as inflows to these reservoirs, and the water supplied from these reservoirs to consumers as the product. Change over time in water yield or inflows was determined from age of the forest. Analysis of the data in the carbon and water accounts enabled estimation of current and potential ecosystem services of carbon sequestration and water yield under different management scenarios.

The biodiversity accounts demonstrated spatial dependencies by relating animal abundance, diversity, threat status and ecosystem characteristics to the land account. Ecological monitoring data was used to apply the IUCN Red List of Species and Ecosystems in the accounting framework. Trends in biodiversity in relation to ecosystem condition, change over time, and threshold states were used to inform policy about requirements for habitat in protected areas. Testing the application of these

site data in the accounts showed how to generate value from existing data, as well as informing future design of monitoring programs.

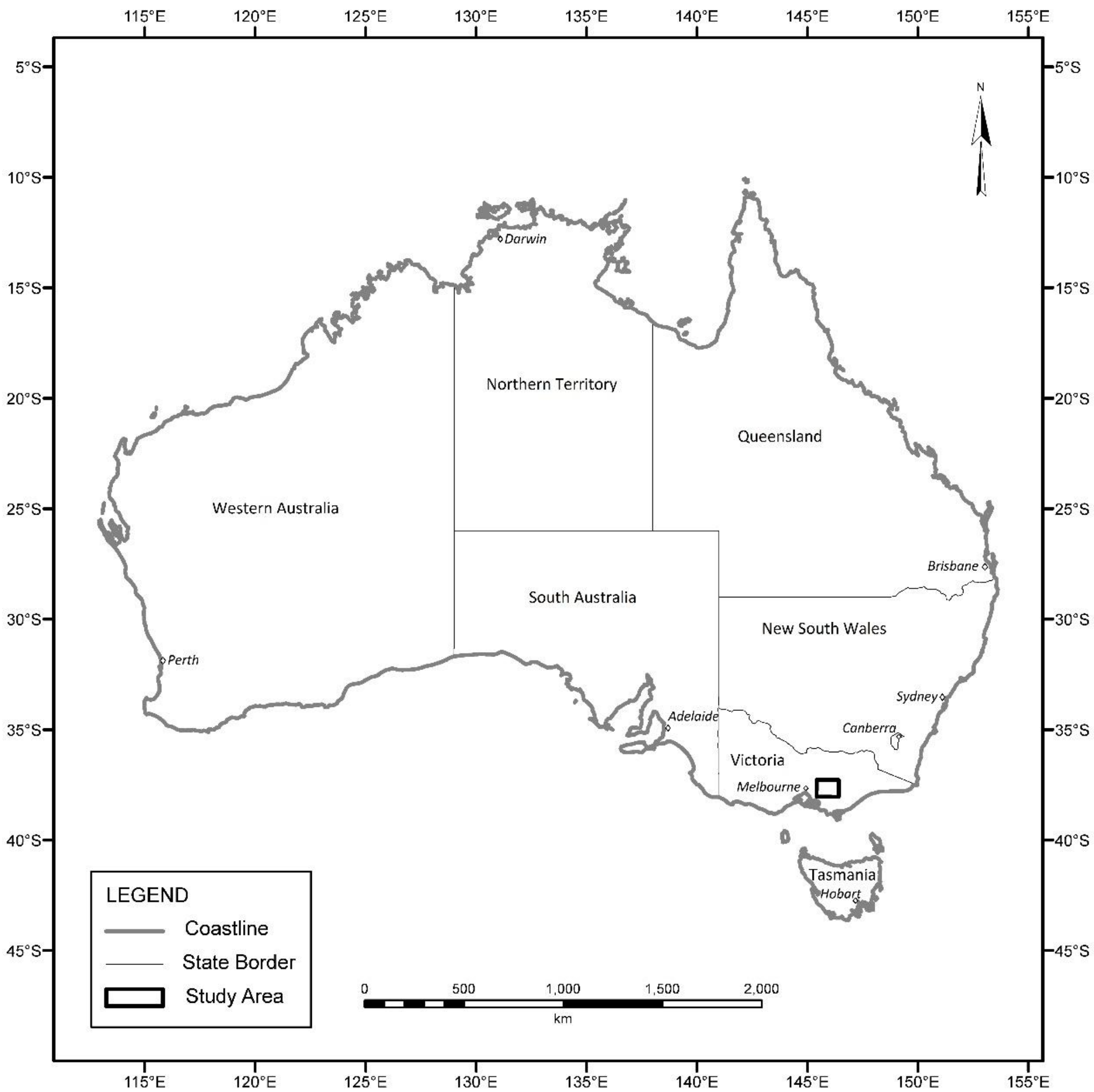
We demonstrate how results from ecosystem accounts that include condition, change over time relative to a reference state, and comparison of alternative land use activities, are used to inform current land management controversy. Additionally, such analyses can be used to inform progress towards targets in the Convention on Biological Diversity Aichi Targets and the United Nations Sustainable Development Goals.

Introduction

Input data for ecosystem accounts are derived from different sources, scales, unit delineations, levels of accuracy, classifications, units, aggregations, spatial representations and geographical areas. An objective of accounts is selection and synthesis of data to produce outputs relevant to natural resource management decisions. The key process in using data to develop accounts is scaling, both spatially and temporally, to align with the area and timeframe of study.

Integration and scaling of data often do not form a linear process. Site data need to be combined with spatial data and understanding of ecological processes to produce outputs at appropriate spatial and temporal scales. Hence, flexibility is required within the accounting framework to accommodate these differences in scales.

Based on a case study of ecosystem accounts for the Central Highlands region in Victoria, Australia (Figure 1)(Keith et al. 2017), we demonstrate some of the challenges and methodologies for scaling data, comment on the research agenda and technical recommendations for experimental ecosystem accounting, and suggest some areas of future development of accounting systems.



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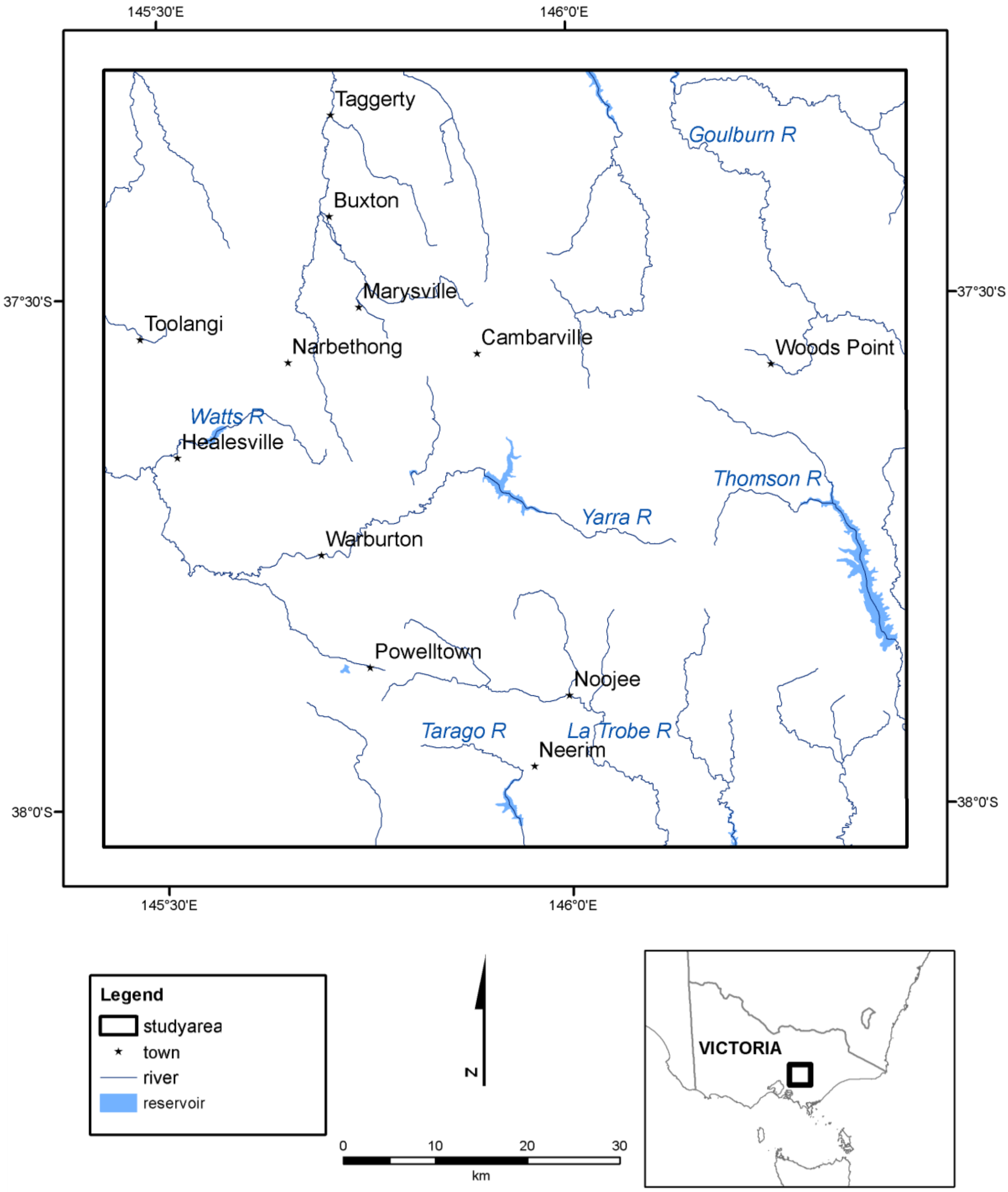

Figure 1. Location of the Central Highlands study area, approximately 100 km northeast of Melbourne, the capital of Victoria, Australia.

Spatial representation of data via land accounts

Land accounts integrate the spatial information about land cover and land use, and provide information about the extent of ecosystems. Land cover links to both the production and use of ecosystem services. In this way, the land cover account links ecosystem characteristics to economic agents, which are aggregated to industries, and presented in land use accounts.

In addition, ecological site data need to be scaled up across the landscape to cover the range in environmental conditions that influence ecosystem extent and condition for the area of study or the Ecosystem Accounting Units as they are known in the SEEA-Experimental Ecosystem Accounting (SEEA-EEA, UN et al 2014). The appropriate spatial scale of the data and boundary of the study area are dictated by the management questions being addressed. A scale often applicable to land management decisions is a region, such as a catchment, biogeographic region, ecological community, local government region, etc. The level of detail of the input data and spatial resolution will depend on the size of the study area and outputs required.

In combining different sources of spatial data for land cover, land use, disturbance history, as well as land tenure and land management, we found many discrepancies. The land account is the critical base for other accounts, and so ensuring its accuracy and consistency are priorities. A system for validation and ground truthing of remotely sensed data is paramount and local knowledge of the region is highly desirable. Resources to identify and correct errors in the basic spatial data will always have limitations. Hence, setting criteria to prioritise each type of spatial data and defining their order of application provides a consistent process. Deciding on the prioritisation is based on knowledge of the datasets and their relative importance for the management questions.

Temporal representation of land accounts

Quantifying change over time in ecosystem extent and condition is a key component of ecosystem accounting. This change often results from a change in land use that causes a change in land cover or ecosystem extent, for example clearing of forest and conversion to agricultural land. However, changes in ecosystem condition, with no change in land use or land cover, also can have significant impacts. In the land accounts, we incorporated ecosystem condition to produce a three-way matrix of land cover, ecosystem condition and change over time (Figure 2). In addition, within land cover types (wet mixed forest, open mixed forest, alpine ash, mountain ash, rainforest, woodland, montane woodland), we separated land use types (conservation, production forestry) and disturbance types (wildfire, logging) for some analyses to attribute changes in condition to land use activities.

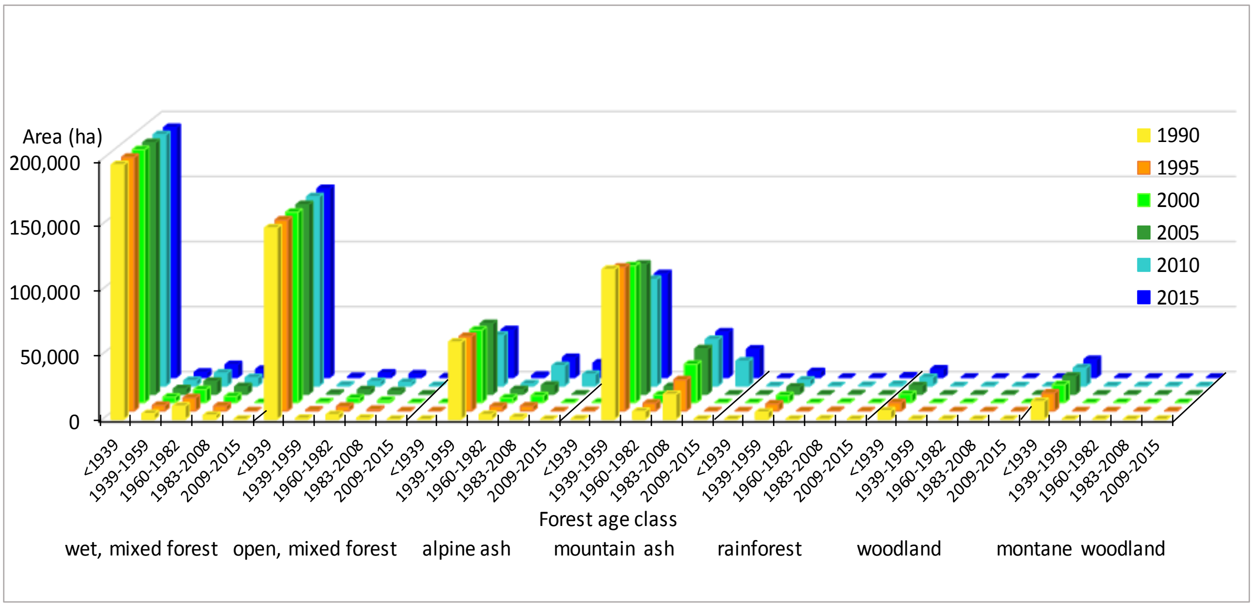

Figure 2. Change in area of each forest type (land cover type) and age class (indicator of ecosystem condition) over time from 1990 to 2015.

Assessing change over time in ecosystem assets and services requires information about ecological processes to derive ecosystem production functions, for example processes of growth, mortality, decomposition, emissions and runoff. These processes vary in relation to environmental conditions (e.g. rainfall) and disturbance events (e.g. fire or logging).

Data need to be scaled over time to determine the difference between current ecosystem extent and condition from a reference state. At its simplest, the reference state may be set as a date in time. For example, in Australia 1750 is sometimes used as a reference state time (e.g. Vardon et al 2016), this being a time of pre-European colonisation of Australia. Condition may also be linked to the supply of ecosystem services (Hein et al 2016). Understanding the drivers of these potential changes is critical for assessing the consequences of alternative land use activities.

Ecosystem condition

The concepts of condition and appropriate reference states are best applied to specific ecosystem assets and their supply of services. Condition is assessed using specific indicators, depending on the ecosystem assets and services they describe. Indicators of ecosystem condition used in accounts will be most effective when they are designed to answer specific management questions. Appropriate indicators will vary depending on the ecosystem type, spatial resolution of the study, and management questions. For example, indicators of condition related to specific Sustainable Development Goals or Aichi Targets will be different. Guidance on a range of possible indicators for different ecosystems and objectives would be a useful output from the SEEA EEA revision process.

The key indicator of forest ecosystem condition used in Central Highlands was age of the forest since disturbance. The disturbance may be due to natural or human activities and is determined from the disturbance history of stand-replacing events, in this case by wildfire and logging. High severity wildfire kills montane ash forest but not mixed species forest. The logging practice is clearfell logging and slash burning of both forest types, resulting in even-aged regeneration. Forest age influences water yield, carbon storage, biodiversity, timber production and tourism.

The SEEA-EEA notes several characteristics of ecosystem condition, including vegetation, soil, carbon, water and biodiversity. Below we describe the measurement of condition related to both the supply of ecosystem services and characteristics of water, carbon and biodiversity relative to the age since disturbance (rather than a pre-determined point in time).

Carbon accounts

Accounts of carbon condition were developed using a reference state defined by disturbance history. Biomass carbon stock density (tonnes carbon per hectare) was calculated at 54 sites from measurements of biomass components – living and dead trees, understorey, litter, coarse woody debris, and estimated belowground biomass. These sites were selected in a stratified random design to cover a range of forest types and ages. Additionally, inventory data from 930 georeferenced sites were used to calibrate a biophysical model that related carbon stocks to spatial data for environmental variables, forest type and disturbance history. For other land cover types, best estimates of biomass carbon stock density were derived from the literature. The model was used to estimate biomass carbon stock density spatially across the landscape (Keith et al. 2014a).

The spatial model estimated carbon stocks in a specific year (2009). To determine change over time in carbon stocks, we included ecological production functions to describe the processes of tree growth (specific for each forest type), mortality, decomposition, collapse of dead standing trees, emissions from fire, and losses from harvesting (Figures 3 and 4). Carbon stocks were projected forward from 2009 to 2015, and backwards from 2009 to 1990, based on these functions and the disturbance history of fire and logging. The ecosystem service of carbon sequestration is the positive net change in carbon stock over a time period, usually a year. Net carbon stock change is the balance between additions due to growth and reductions due to decomposition, combustions and removal of stocks off-site.

The carbon condition was derived from a spatial model with calibration sites that were undisturbed. Effects of disturbance events were distinguished between those due to natural and human activities. The carbon condition at a landscape scale was defined as the carbon stock in the ecosystem under prevailing environmental conditions (Keith et al. 2010). Such ecosystems are termed old growth or primary forests. This is distinct from a mature forest at harvest age, where the carbon stock in the Central Highlands forests is approximately half that in an old growth forest (Keith et al. 2014b). The difference in carbon stocks between an old growth forest and the forest at any other age (e.g. harvest maturity) represents a difference in the condition of carbon stock. The carbon condition of the old growth forest was used as the reference state or maximum carbon stock. The net carbon stock change from the reference state corresponds to the potential for carbon sequestration if the forest could continue growing and regain this carbon stock, thus representing the ecosystem service. Including functions that describe ecological processes over time allowed estimation of carbon stock change, and hence the potential for increases or decreases in the supply of ecosystem services. Analysis of the data in the carbon accounts enabled estimation of current and potential ecosystem services of carbon sequestration under different management scenarios.

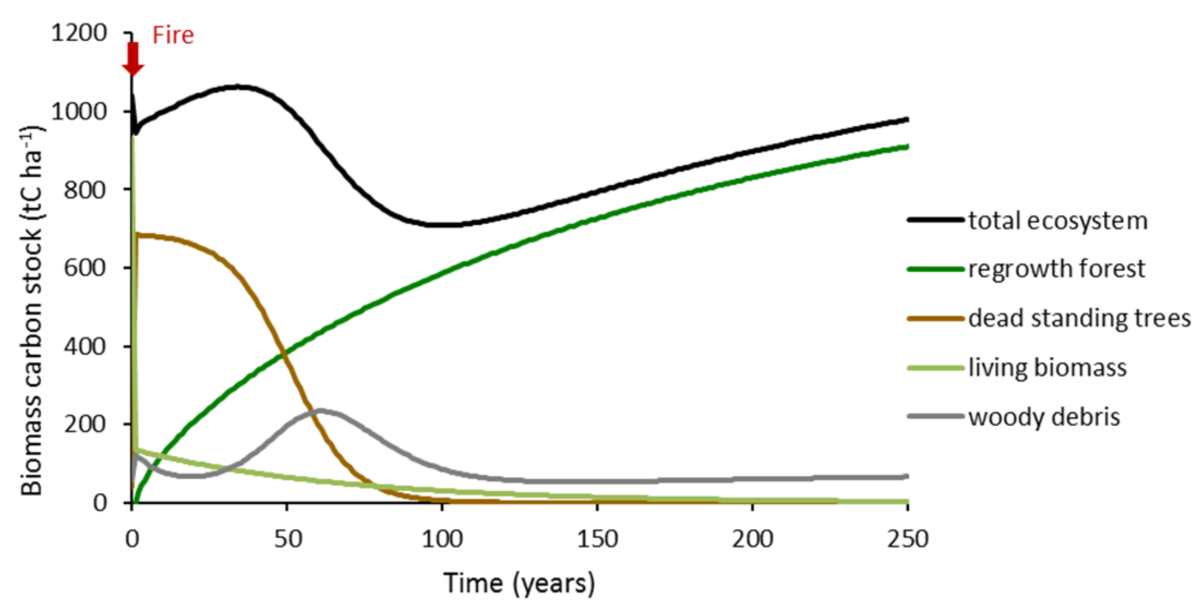

Figure 3. Temporal changes in carbon stocks of biomass components of an old growth forest following wildfire, including processes of emissions in the fire, regeneration, decomposition, mortality and collapse of dead trees.

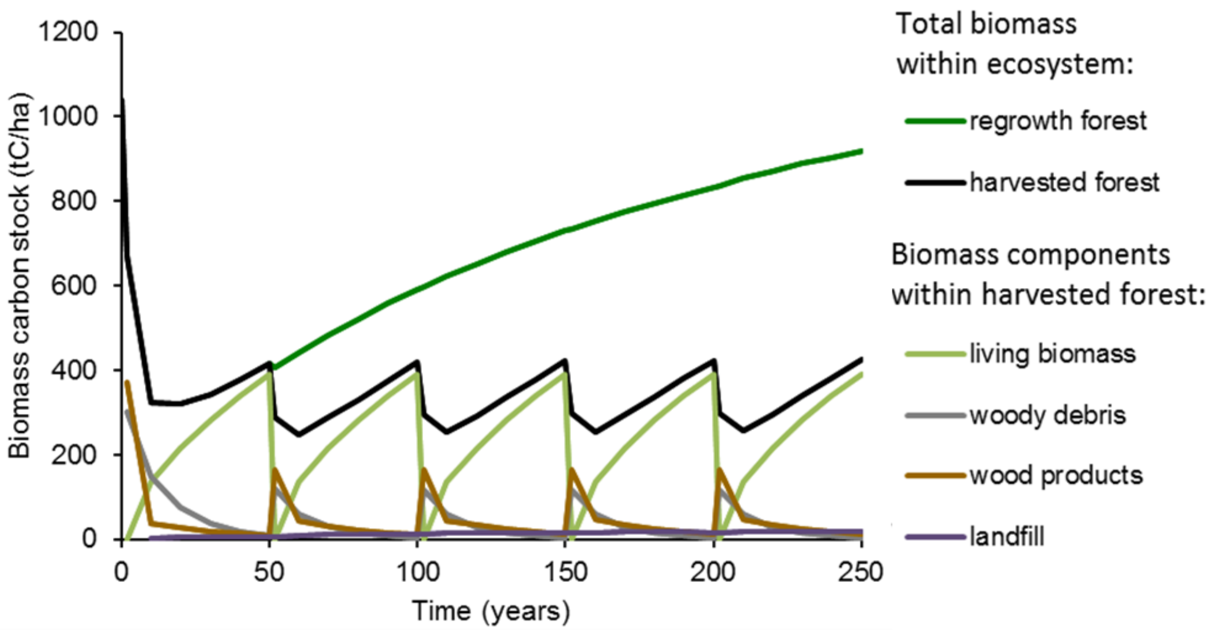

Figure 4. Temporal changes in carbon stocks of biomass components of an old growth forest following clearfell harvesting and slash burning, including processes of emissions in the fire, regeneration, decomposition, mortality, harvesting and removal of wood, longevity of wood products, transfer and longevity in landfill.

Defining a reference state can be complex as it involves attributing natural and human disturbance factors (Vardon et al. 2016) and an understanding of the ecological states of an ecosystem. These states and factors vary among ecosystems but guidance and examples of defining reference states for use in ecosystem accounting would be a useful output from the SEEA EEA revision process.

Water accounts

The water asset account represented the water stored in reservoirs, with the ecosystem service of water provisioning defined as inflows to these reservoirs, and the water supplied from these reservoirs to consumers as the product. Water yield from the catchments as inflows to the reservoirs was derived from a spatially explicit water balance model that used input data of precipitation, evaporation, soil water storage and landscape position, and was calibrated with gauged streamflow data (Stein et al. 2009).

Changes over time in water yield or inflows occur in response to climate variability, land cover change, and forest disturbance history. Water yield is influenced by the condition of the vegetation, and particularly the age in montane ash forests (species that regenerate from seed and produce dense, even-aged canopies). The response of water yield to forest age was calculated from a model derived from multiple catchment-scale empirical data (Kuczera 1987) (Figure 5). This ecological production function enabled estimation of the temporal dimension of the ecosystem service of water yield, in response to increasing age of the forest and regeneration following disturbance events. The spatial distribution of water yield across the landscape showed reduced yield in areas with young forest regenerated after fire or logging.

Figure 5. Reduction in water yield in montane ash forest estimated as a proportion of the pre-disturbance amount in old growth forest (Kuczera 1987) and regrowth forest (derived).

The water asset account was determined from change over time, but not assigned a condition metric. Water yield was assessed in terms of the condition metric of forest age and the reference state as either old growth forest or regrowth forest at harvest maturity (75-year-old), and presented as change over time in relation to forest type and age. This information was used to analyse the potential difference in water yield if logging had not occurred and reduced the yield. This analysis of water yield covered the distribution across the entire landscape of the study area. The ecosystem service of water provisioning was limited to the water yield in the catchments that provided inflows to the reservoirs.

Biodiversity accounts

Accounting for biodiversity in terms of composition, structure and function and by applying consistent classifications over time to identify changes in the size populations, distribution or extent, threatening processes, and extinction risk is an evolving area. Lack of a single indicator or aggregation of data that defines biodiversity makes developing biodiversity accounts and biodiversity condition difficult. Some progress has been made (e.g. King et al. 2016) but much remains to be done.

For many ecosystems and management decisions, use of specific data to inform questions will be more relevant than use of general indicators. Insufficient data about all taxa in most regions precludes development of general species abundance accounts for all Kingdoms, either as annual change or comparison with a reference state. Even where national syntheses of biodiversity have been compiled, such as the Atlas of Living Australia, the records are not sufficiently representative to allow definitive comparisons between locations or times. Some taxa are greatly under-represented, particularly invertebrates, as well as lower orders. The nature of change in biodiversity that the accounts would aim to reveal is mostly abundance of individuals within species or relative composition, rather than gains or losses of species.

Collection of data on biodiversity is resource-intensive and usually specifically related to a research question. An objective in accounting is to integrate different sources of data to provide spatial and temporal coverage of the study area. In the Central Highlands, long-term research on biodiversity provided an exceptional dataset, but was limited to one group of animals – arboreal marsupials. We used the available data to develop four types of biodiversity accounts. These provide only a small piece of a much larger picture, but do indicate trends over time and in response to human land use activities that are relevant to management decisions.

Accounts for threatened species within the Central Highlands showed the change over time in the numbers of species listed (based on the Australian Environmental Protection and Biodiversity Conservation Act 1999 (DotEE 2016) and the IUCN Red List 2012). Condition of biodiversity was assessed in terms of the number of species classified as threatened, the threat categories, and the change in categories over time. The number of critically endangered species has increased in the last 5 years. The change in threat category of a species represents change in the extinction risk of that species. These changes may be indicative of the direction of change in ecosystem condition related to more general biodiversity of the study area. Caveats to interpretation of these results include the fact that numbers of species listed increase as more research and inventory are performed, systems of classification differ in their criteria and hence listings, listings are based on nomination rather than comprehensiveness or representativeness, and updates of listings are infrequent.

Accounts for seven species of arboreal marsupials (possums and gliders) were derived from 28 years of annual monitoring data of animal abundance within 1 ha sites located in different forest age classes. This monitoring programme is part of the Australian Long-Term Ecological Research Network (LTERN). Forest age was related to change in abundance of species. This account provided the most definitive evidence of impacts of logging on biodiversity. However, these results are site specific and not available in other regions. Relating detailed data about animal abundance to habitat attributes provided a basis for scaling up these data both spatially and temporally. The key habitat attribute for arboreal marsupials, as well as many birds and invertebrates, is the presence of large, old hollow-bearing trees to provide nest sites (Figure 6). Monitoring the number of hollow-bearing trees in different forest age classes and their change over time is more feasible than observing nocturnal animals.

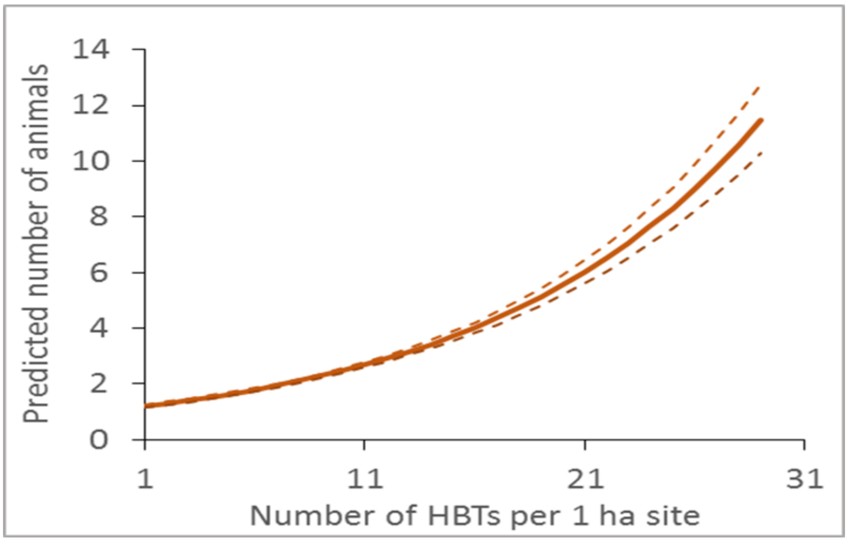

Figure 6. Number of arboreal marsupial animals related to number of hollow-bearing trees per 1 ha site.

Accounts were developed for the abundance of hollow-bearing trees in different forest age classes in the 1 ha monitoring sites. The more hollow-bearing trees the better the condition of the forest for the species that depend on hollows. The number of hollows was greater in forests with a longer time since disturbance. This account provided evidence about the impact of land use activities. Further work on the variability of tree abundance within forest age classes would assist scaling up these data to develop a spatial distribution of hollow-bearing trees across the landscape. Spatial distribution of the occurrence and abundance of animals is even more complex, involving habitat suitability for nest sites, food sources and movement; bioclimatic domain; landscape context of the habitat; dispersal; reproductive capacity; competition and population dynamics.

An aggregation of biodiversity data and other data was used to develop an ecosystem risk assessment using the IUCN's Red List of Ecosystems criteria (IUCN 2017). A risk assessment requires an assessor to identify the defining features of the system and the processes that threaten them, to evaluate trends in key variables relevant to the persistence of the ecosystem, and to predict the likelihood of ecosystem collapse within 50 years.

The Red List system provides a framework to examine different types of data, from various sources, and to address specific criteria designed to assess different types of risks to ecosystems. There are five criteria (A-E) with the first four having three sub-criteria requiring an assessment relative to past, current and future scenarios. For all criteria, numerical thresholds define ordinal categories of threat from Least Concern through to Critically Endangered. The final, overall ranking is determined by the most severe ranking (refer Keith et al. 2013), however, criterion E is an overarching analysis of the impacts of biotic variables on the probability of ecosystem collapse within 50-100 years. For the forests in the Central Highlands, the overall ranking for the ecosystem was Critically Endangered (Burns et al. 2015).

Notably, criteria that could be assessed using remote sensing data were less sensitive indicators of risk than criteria that required empirically collected biotic data. For example, ecosystem extent, distribution, size, area of occupancy and number of locations showed little reduction over the past 50 years and was therefore classified as Least Concern under criteria A and B. However, evidence from time-series site data showed severe disruption to forest structure and associated biotic processes, resulting in a Critically Endangered ranking under criterion D. This was due to a positive feedback between logging and fire (Taylor et al. 2014), which significantly impairs the development of old growth forest structure (Lindenmayer et al. 2014). Interactions such as these were explicitly assessed through stochastic modelling for multiple scenarios under criterion E (Figure 7). All 39 scenarios modelled indicated a ≥ 92% chance of ecosystem collapse in the next 50 years. Ultimately, the Critically Endangered status is a result of the rapidly declining abundance of large old hollow-bearing trees and the limited current area of old growth forest in the ecosystem.

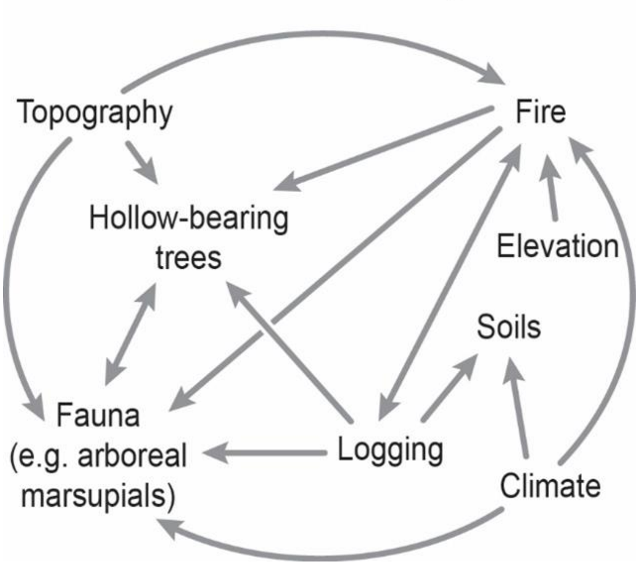

Figure 7. Ecological processes relevant to the assessment threat status of the Mountain Ash ecosystem.

These combined biodiversity accounts demonstrated spatial dependencies by relating animal abundance, diversity, threat status and ecosystem characteristics to the land account. Testing the application of these site data in the accounts showed how to generate value from existing data, as well as informing future design of monitoring programs. Trends in biodiversity in relation to ecosystem condition, change over time, and threshold states were used to inform policy about requirements for habitat in protected areas.

Conclusions

Results from the ecosystem accounts in the Central Highlands included change in condition relative to a reference state, and this information was used to analyse effects of different activities. These results allowed quantification of levels of degradation and restoration of ecosystems, which was used to inform management decisions about trade-offs between different land use activities.

Ecosystem condition may be derived from the deviation of an ecosystem asset from a reference state, or from the supply and use of ecosystem services. The characteristics of ecosystem condition, and the indicators used for measurement, may be similar or different between different assets. Indicators and metrics used for ecosystem condition are related to the specific objectives of the accounts.

We found that analyses of change in condition over time and potential change under scenarios of different land management were best achieved using a reference state defined by time since disturbance, either natural or caused by human activity. We agree with Recommendation 4.63 that selection of an appropriate reference state may vary with the ecosystem and management question. Where a natural ecosystem is too difficult to define, an historical baseline or condition based on time since disturbance may be appropriate.

Consideration of the supply and use of ecosystem services may be appropriate for some land covers and land uses such as agriculture, plantation forestry and urban areas, but definition of condition in this way would mean that ecosystem services not used by human activities would be assigned poor condition.

We support Recommendation 7.68 that ecosystem degradation can be defined in terms of change from a reference state. The reference state needs to be defined carefully and explicitly for the specific ecosystem, type of accounts and management questions.

Our regionally-based ecosystem accounts highlighted the utility of specific indicators of ecosystem condition to address specific management questions, in preference to an aggregated index, as suggested in Recommendations 4.62.

The overlap but differences in definitions of the SEEA Central Framework and Experimental Ecosystem Accounts causes some confusion and potential impediment to adoption of accounting. Ecosystem accounts, as an additional perspective to environmental accounts, incorporate interaction of natural processes within a spatial area. Where similar components are used for both accounts, they could be linked more easily by using the same, or closely aligned, terminology. For example, ecosystem extent is based on land cover from the land accounts.

Questions to the London Group:

1. Are there other known studies that define ecosystem condition in way similar to "time since disturbance"? Is this considered a potentially useful indicator in other circumstances?

2. In the current guidelines for ecosystem accounts, it appears that condition can be defined in two ways: (i) supply of ecosystem services, and (ii) ecosystem assets relative to a reference state. Should these two cases be described by different terms?

Our analysis of carbon accounts in the Central Highlands illustrates a case where separate definitions may be appropriate. The climate change abatement benefit of forests is their storage of carbon in the land sector rather than the atmosphere. The metric appropriate for assessing abatement is net carbon stock change, and this metric is used for assigning carbon credits. Net carbon stock change represents a change in the ecosystem asset relative to a reference state. The example of a forest ecosystem is that the carbon stock in a regrowth forest is lower than the stock in an old growth forest, and hence has a lower ecosystem condition. The metric associated with supply of ecosystem services is that of carbon sequestration, that is the rate of flow of carbon uptake by the forest. A fast-growing regrowth forest may have a high rate of carbon sequestration (or primary productivity), but this is not an appropriate metric of condition in terms of climate change abatement because it does not account for the loss in carbon stock from the regrowth forest (Ajani et al. 2013, Mackey et al. 2013). Hence, we consider it important that these two metrics have separate definitions and terms so that they are not both used as comparable indicators of condition.

3. A "sustainable yield" providing ecosystem services can be a subjective definition, and dependent on perspective (condition for nature or for human use). Should such an indicator be included in accounts that are an information system, and interpretation is performed at a later stage?

4. Is there a difference between ecosystem extent and land cover extent? Using the same term in environmental accounts and ecosystem accounts would improve consistency and linkages between these accounts.

5. As part of the analysis of the results from the accounts for the Central Highlands, we modelled changes in ecosystem services (net carbon stock change and water yield) in the counterfactual case – as if forest logging had not occurred. The rationale was to use the historical data in the accounts and not project future changes with unknown variables, such as climate change. Is this considered a useful form of analysis to identify trade-offs between land use activities in their use of ecosystem services?

6. Spatial units are related to classification systems and how available data can be integrated within these classifications. We found the most limiting component was the highly aggregated form of government financial data (Australian Bureau of Statistics and Australian Bureau of Agricultural and Resource Economics) and the inability to obtain data from private enterprise. These data limitations meant that land use could be linked only to the highest level of classification of ecosystem services (CICES). Are there suggestions about how to quantify lower levels of ecosystem services?

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