

14 **Abstract:**

15 Decisions about natural resource management are frequently complex and vexed, often
16 leading to public policy compromises. Discord between environmental and economic metrics
17 creates problems in assessing trade-offs between different current or potential resource uses.
18 Ecosystem accounts, which quantify ecosystems and their benefits for human well-being
19 consistent with national economic accounts, provide exciting opportunities to contribute
20 significantly to the policy process. We advanced the application of ecosystem accounts in a
21 regional case study by explicitly and spatially linking impacts of human and natural activities
22 on ecosystem assets and services to their associated industries. This demonstrated
23 contributions of ecosystems beyond the traditional national accounts. Our results revealed
24 that native forests would provide greater benefits from their ecosystem services of carbon
25 sequestration, water yield, habitat provisioning and recreational amenity if harvesting for
26 timber production ceased, thus allowing forests to continue growing to older ages.

27

28 Ecosystem accounting has the potential to contribute to the policy process by re-framing
29 debates about natural resource management^{1,2}. Accounts help circumvent polarised
30 arguments about the relative importance of environmental versus economic factors by
31 systematically and regularly assessing the costs and benefits of changing ecosystem assets
32 and services. Accounting involves quantification, both spatially and temporally, in physical
33 terms that can be linked to monetary values. By incorporating a range of ecosystem services
34 in the accounts, the analysis becomes broader than the often two opposing viewpoints. Such
35 an approach may facilitate a convergence of opinion about the need for change, by
36 demonstrating explicit comparisons between land uses, and a process for change by
37 quantifying physical and monetary metrics³. Finding solutions to conflicting land uses
38 becomes a process of maximising benefits for public good, not only economic growth and
39 private gain. Hence, ecosystem accounts may be critical for setting agendas for natural
40 resource management at many levels: regional land use conflicts; national policies such as
41 State of the Environment report recommendations; and international agreements such as the
42 Sustainable Development Goals⁴.

43 The System for Environmental Economic Accounting (SEEA)⁵ is an internationally agreed
44 statistical standard for combining environmental and economic information in a form
45 appropriate for policy-makers. This system provides a standard model for the policy process
46 in which the production boundary of the economy lies within the environment. Accounts are
47 a system of organising information in which measurement of environmental – economic
48 relationships can be described in physical or monetary terms. Ecosystem accounting⁶ includes
49 contributions of ecosystems to the environmental – economic system, which are linked
50 explicitly to economic activity and human well-being. Ecosystem accounts synthesize data on
51 all assets, goods and services, both those accounted for within the economic system, and in
52 particular the System of National Accounts (SNA) that produces the aggregate Gross

53 Domestic Product (GDP)⁷, and those that lie outside this system as unrecognised
54 contributions of ecosystems to economic activity and human well-being³. A model of the
55 environmental-economic system (Figure 1) shows the stocks and flows of natural resources,
56 and the stages at which quantification in physical and/or monetary terms can be applied to
57 make comparisons.

58 Ecosystem accounting provides information for decision-making about trade-offs between
59 the economy and the environment, and activities within the economy, as well as evaluating
60 trends over time and management options⁸. Indeed, ecosystem accounts have shown that
61 gains in environmental benefits can be achieved alongside economic growth⁹. However,
62 demonstrating the utility of accounting for specific decisions has been difficult^{10,11,12}, and is
63 probably best tackled at the scale of a region in which decisions are made. The technical
64 nature of accounting is often poorly understood by policy-makers and their reluctance to
65 engage with accounting may result from the difficult choices revealed¹⁰. Ecosystem services
66 constitute one component of the SEEA; they have been ascribed financial values^{13,14} and
67 applied to comparisons of multiple land uses¹⁵, but it has been similarly difficult to
68 demonstrate their direct application to decision-making¹¹.

69 Here we present a key advance in ecosystem accounting by linking spatially quantified
70 ecosystem assets and services with their contributions to industries, in a form consistent with
71 the SNA⁷, as well as identifying contributions of ecosystem services not included in the SNA.
72 Such ecosystem accounts have a broad application for informing land use and meso-scale
73 economic management decisions because many sources, types and scales of information are
74 integrated. Information includes collections of economic units, such as businesses to
75 industries, capital within and outside the SNA, biophysical characteristics and processes
76 across the landscape, and relationships between ecosystems and the services they provide for
77 human benefits. The accounts are comprehensive in terms of the economic activities,

78 ecosystem assets and services, and their spatial context within the landscape, which are
79 relevant to the land management decisions for the region. Integration of data across scales to
80 present information at the regional or meso-scale is key for government decisions about land
81 use change, as distinct from information relevant to local business decisions or national
82 accounts. The accounting approach uses exchange values, which distinguishes it from other
83 estimates of the value of ecosystem services^{16,17} Estimating exchange values for ecosystem
84 services means that the contribution of these services can be seen in the national accounts,
85 compared with the current situation where they are hidden or ignored.

86 Our accounts were derived from detailed site and remotely sensed biophysical data and
87 ecosystem-specific functions, together with economic data obtained from existing national,
88 sub-national and business accounts. The accounts are presented at spatial and temporal scales
89 relevant to land management decisions: activities undertaken within a region over years to
90 decades. We advanced the application of the SEEA accounting framework by assessing the
91 contributions of ecosystems at three levels of the environmental-economic interaction
92 relevant to management issues: (i) ecosystem services, both currently measured and
93 previously unrecognised in the national accounts; (ii) economic uses of ecosystem services by
94 industries as their contribution to GDP, as measured by an industry value added (IVA) metric
95 (the sum of all IVAs equals GDP); and (iii) gains and losses in IVA and ecosystem services
96 involved with trade-offs between land uses. The key outcome was the capacity to quantify
97 ecosystem services and their contribution to industries, and hence explicitly reveal the trade-
98 offs required when use of services by different industries conflict. The accounting framework
99 facilitates comparisons of values, but does not necessitate payment for the services.

100 We demonstrate the advantages of using the ecosystem accounting approach, based on the
101 above three levels of environmental-economic interaction, to inform decision-making in a
102 case study region: the tall, wet forests of the Central Highlands of Victoria, Australia (see

103 Methods). Ecosystem accounting provided a valuable method for informing land
104 management policy about complex issues and within the timeframe for decision-making. The
105 accounts were applied spatially at the regional scale and were inclusive of the main activities
106 and services in the region, rather than studies of polarised activities and their specific
107 services, or restricted to the goods and services currently in the SNA and used in economic
108 analysis.

109 Issues of native forest management in the Central Highlands are common to many regions
110 globally where productive uses of ecosystem assets conflict with conservation objectives.
111 Ecosystem services occurring within the region were identified and located spatially (Figure
112 2). Monetary valuations were assessed for provisioning services of water, timber from native
113 forest and plantations; regulating services used in the production of crops, fodder and
114 livestock; cultural and recreational services; and regulating services of carbon sequestration.
115 Additionally, the habitat provisioning services for biodiversity were assessed using physical
116 metrics (see Methods). Selection of the ecosystem services was based on the ecosystems
117 occurring within the region, characteristics of their ecosystem services, and the decision-
118 making context¹⁸. Classification of the ecosystem services used the international standard
119 from CICES¹⁹, with the addition of habitat provisioning services.

120 Results

121 The accounts revealed that the greatest values of ecosystem service were derived from
122 provisioning for water and regulating services used in agricultural production and for carbon
123 sequestration, with the lowest value from native forest timber provisioning (Figure 3a). The
124 contribution to GDP of the associated industries showed even greater differences between
125 industries, with the economic value of agricultural production, water supply and tourism an
126 order of magnitude above that of native forestry (Figure 3b).

127 Trade-offs are required when the same resource may be used for more than one purpose,
128 especially if uses are mutually incompatible, or the use of one resource affects the condition
129 of other assets, or the same type of asset in different areas. An example in our case study
130 relates to the impact of native forest timber harvesting on reducing forest age, which
131 decreases the ecosystem condition of the forest for water yield and carbon storage, as well as
132 biodiversity and recreational services. Trade-offs in physical and monetary terms of
133 ecosystem services and IVA were derived from analyses of the counterfactual case; the
134 difference in services if harvesting had **not** occurred (Table 1, Figure 4). This analysis
135 allowed comparison of the losses from ceasing native forest timber harvesting with the gains
136 in carbon sequestration, water yield and habitat provisioning, if forest growth continued
137 leading to greater forest age. Data were available for these ecosystem services to assess the
138 differences between harvested regrowth forest and old growth forest.

139 Gains in water yield would occur if forests continued growing without harvesting, because
140 young, regenerating forests have higher rates of evapotranspiration than older forests. The
141 reduction in water yield in regenerating forest is up to 29% in 1939 regrowth that is
142 harvested, and up to 48% in old growth forest that is harvested (Supplementary Figure 1). In
143 the area that has been logged, the reduction in water yield was estimated to be an average of
144 10.5 GL yr⁻¹, equivalent to \$A2.5 million yr⁻¹. This water yield would be gained if the forests
145 were allowed to continue growing rather than being harvested.

146 The carbon sequestration potential of ceasing native forest timber harvesting and allowing
147 continued forest growth was estimated to be 3 tC ha⁻¹ yr⁻¹ (averaged over 1990 – 2015),
148 which is equivalent to \$A134 ha⁻¹ yr⁻¹. Over the area of forest that has been logged, this
149 potential increase in carbon stock is 0.344 MtC yr⁻¹, equivalent \$A15.5 million yr⁻¹ (Table 1).

150 Gains occur in habitat provisioning services for biodiversity through improved ecosystem
151 condition of older forests. Old growth forests have an average number of hollow-bearing
152 trees (HBTs) of 12.1 ha⁻¹ with similar rates of losses and gains of trees. Regrowth forests
153 after logging have an average of 3.6 HBTs ha⁻¹ with a nearly five-times greater rate of loss of
154 trees than gain over the 28-year monitoring period. The potential gain would be 8.5 HBTs ha⁻¹
155 ¹ if harvesting ceased and the forest was allowed to continue growing to an old growth state
156 (Table 1). Metrics of biodiversity and habitat provisioning services indicated an overall
157 decline in state and condition of populations and their habitat. Species accounts showed an
158 increase in the number of threatened species and severity of their threat class. Numbers of
159 arboreal marsupials declined, along with the number of HBTs on which they depend. The key
160 threatening process for these animals is the accelerated loss of HBTs in younger forests and
161 the impaired recruitment of new trees due to native forest harvesting²⁰.

162 Accounting for carbon sequestration and water yield alone revealed a small net loss in the
163 value of ecosystem services (-\$A0.7 million yr⁻¹), if harvesting had not occurred. The trade-
164 offs in carbon and water were quantified (see Methods), and were considered as known gains
165 (Figure 4a). However, ecosystem services used for culture and recreation, agricultural and
166 plantation timber production, which currently account for about half the total value of
167 ecosystem services, would also very likely increase and more than account for the difference.
168 Trade-offs in cultural and recreational services and plantation timber provisioning were
169 estimated and considered as potential gains, with a low and high range in their values (Figure
170 4a). Estimated values of ecosystem services were based on information about the potential
171 expansion of tourism if a larger area of native forest was protected²⁰, and substitution of
172 wood products by plantations. Native forest timber harvesting does not directly affect
173 agricultural production because they occur on different areas of land.

174 The trade-off in habitat provisioning services is a known gain that was quantified (Table 1),
175 but not valued in monetary terms. Economic valuation of habitat provisioning and
176 biodiversity is problematic and not attempted in this study, although has been done
177 previously using welfare values²². The species within the study area clearly have value, as
178 evidenced by the efforts made to conserve many of them, for example, listing them as
179 endangered under various laws and the expenditure on their protection. However, the best
180 way to record this in ecosystem accounting is not yet clear in the SEEA.

181 Accounting for the difference in IVA due to trades-offs, the increase in economic activity
182 from water yield and carbon sequestration (under a potential market) as known gains, surpass
183 (+ \$A8.5 million yr⁻¹) the loss from native forest timber production (Figure 4b). The addition
184 of potential gains from tourism and plantation production further increase IVA.

185 Spatial distributions of ecosystem services of water provisioning, timber provisioning and
186 carbon storage were derived and displayed as indices (Supplementary Figures 2 – 4). These
187 indices were combined to derive an interaction index (see Methods) that shows areas of
188 common highest values of these ecosystem services, or ‘hotspots’ (Figure 5a). The area of
189 conflict is shown within the current land management tenure where the forest is available for
190 harvesting (Figure 5b). Mapping these ‘hotspots’ identified the locations where trade-offs in
191 the use of ecosystem services are required.

192 Discussion

193 Our application of ecosystem accounting provided new insights and understanding of
194 complex trade-offs between competing land uses. Specifically, our approach enabled:

195 (i) *The contribution of ecosystem services to industries to be quantified in physical and*
196 *monetary terms so that the services providing the greatest benefits could be identified, and*

197 ***included in criteria for management decisions.*** In the Central Highlands region, water
198 provisioning services, regulating services used in agricultural production, carbon
199 sequestration, and cultural and recreational services should be prioritised, whereas, native
200 timber provisioning services had the lowest value.

201 (ii) ***Greater transparency of costs and benefits by explicitly identifying ecosystem services***
202 ***that are subsidised.*** For example, water supply in the Central Highlands is subsidised through
203 a fixed price and timber through low returns on investments made by government. The
204 benefits of these subsidised activities can be assessed in terms of efficient use of government
205 funds and identification of beneficiaries.

206 (iii) ***Identification of complementary or conflicting activities.*** Water supply, carbon
207 sequestration, biodiversity conservation and nature-based tourism are complementary
208 activities in the Central Highlands (agriculture and plantation forestry are located on different
209 areas of land). Conversely, native forest timber production reduces the condition and value of
210 forest assets for other activities.

211 (iv) ***Identification of additional policy and market instruments required to improve***
212 ***resource management.*** For example, carbon sequestration in native forests is an ecosystem
213 service that occurs and benefits the public, but currently has no market because it is not
214 included in Australian government regulations. Applying a market price for carbon in the
215 case study identified the potential benefit of native forest protection as a carbon abatement
216 activity.

217 Ecosystem accounting provides information about the stocks and stock changes of ecosystem
218 assets and services, which can be quantified in physical and/or monetary terms. Monetary
219 valuation of ecosystem services is a contentious issue²³ because there are many

220 characteristics of ecosystems that are not valued within the economy. Monetary valuation in
221 ecosystem accounting is done for the purpose of comparison with national accounts.

222 This approach provides decision-makers with clear trade-offs. In the Central Highlands, a key
223 question for decision-makers is whether reducing the risk of extinction of Leadbeater's
224 Possum is worth the \$A12million yr⁻¹ that would be lost in IVA from the native forest
225 industry if harvesting ceased. These economic losses could be offset by increases in the value
226 of water provisioning and carbon sequestration. Down-stream uses of native forest wood
227 products could have alternative inputs, for example, use of plantation timber and recycled
228 paper. This analysis of trade-offs presents a concrete choice. It is different to the type of
229 decision that could be made using contingent valuation²², which estimated the welfare value
230 of Leadbeater's Possum at \$A40 - 84million yr⁻¹ in 2000 (\$A58 - 121million yr⁻¹ in 2015).

231 Monetary valuations in accounting do not necessarily assume substitutability among goods
232 and services. Indeed, the estimated values of ecosystem services demonstrate their high value
233 compared with the costs, and often impracticality, of technological substitutes²⁴.

234 Additionally, monetary valuation represents a minimum derived from the part of the
235 ecosystem service that can be converted to a monetary metric. It does not include other
236 services related to aesthetic, social, cultural, intrinsic or moral benefits. Protection of
237 ecosystem assets and maintenance of flows of ecosystem services involve complex
238 relationships and synergistic properties that cannot be entirely simplified in terms of
239 monetary valuations^{23,24}. Thus, monetary valuations of ecosystem services should be used
240 judiciously in decision-making, recognising their limitations in terms of coverage of all
241 benefits and complexities. The advantage of the ecosystem accounting methodology,
242 comprising both monetary and physical metrics, is to enhance recognition of the contribution
243 of ecosystems to economic activity and human well-being and to start developing a system
244 that incorporates these benefits into decision-making.

245 Because valuations of ecosystem services are not comprehensive, their purpose and
246 appropriate methods of analysis must be clear⁶. Our motivation for analysis based on
247 valuations was to demonstrate alternatives to the current system of land use and the impacts
248 on different beneficiaries. The analysis showed that even partial valuation of some of the
249 ecosystem services provided an economically viable alternative to native timber harvesting.

250 Identification and definition of specific ecosystem services, the criteria for their selection, and
251 appropriate metrics present ongoing challenges for compiling accounts for a region^{23,25}.

252 Comprehensiveness in including all ecosystem services may not be possible in one study, but
253 the relative importance of the services not included must be considered. In the Central
254 Highlands, selection of ecosystem services included in the study was based on long-term
255 research in the region, knowledge of data, and knowledge of land management issues.

256 Additionally, decisions about selection of metrics were pragmatic in terms of using available
257 data; however, data are usually collected for the metrics considered most important by the
258 experts in the field. For example, HBTs ha⁻¹ is considered by ecologists to be a key indicator
259 of suitable habitat for a range of species, and particularly some critically endangered
260 species²⁶. Some of the ecosystem services not included explicitly were water filtration, air
261 filtration, pollination, flood mitigation and soil erosion. Even with the ecosystem services that
262 were feasible to measure in our case study, their contributions to economic activities and
263 human well-being could be demonstrated, and the losses incurred if these ecosystem assets
264 and services did not exist.

265 A particularly important distinction in the selection of appropriate metrics is the stock of an
266 ecosystem asset compared with the flow of ecosystem services from the asset²³. Carbon
267 sequestration presents a good example. The ecosystem service of climate regulation in the
268 land sector is the protection and increase of carbon stocks in vegetation and soils, and hence
269 removal of carbon dioxide from the atmosphere. The appropriate metric is net carbon stock

270 change together with the longevity of the change, rather than the annual rate of change^{27,28}.

271 Assessment of the flow of the ecosystem service must ensure that the stock of the ecosystem
272 asset is not reduced or degraded. Ecosystem accounting includes information about stocks
273 and flows, and both must be considered in valuations.

274 A range of methods for monetary valuation for ecosystem accounting is recommended^{6,29,30}.

275 This is a developing area of research and there are advantages, disadvantages, and
276 practicalities for each method. Valuation of ecosystem services using the resource rent
277 method, as applied in this study for agricultural and plantation timber production, takes no
278 account of the sustainability of service flows. Some service flows may result in degradation
279 or depletion of ecosystem capital, and hence are unsustainable. There is a risk that the results
280 will underestimate the 'true' value of ecosystem services in terms of capturing all the relevant
281 missing prices⁶. This method is not appropriate in the case of open-access resource
282 management because there is no incentive for the owner of the resource to maximise resource
283 rent⁶. The replacement cost method estimates the price of a single ecosystem service and does
284 not have the capacity to include interactions among services, which are in fact an essential
285 characteristic of ecosystems. Trading schemes, such as carbon markets, are subject to
286 variability due to regulatory settings of the market, and may not equate to societal willingness
287 to pay⁶, nor to overall social cost^{31,32}.

288 The accounting approach is different to cost-benefit analysis (CBA) in terms of objectives,
289 methods of valuation, and outputs. In accounting, changes are estimated in the physical extent
290 and condition of assets and the services that flow from them. The results in accounts are a
291 mixed presentation of physical and monetary metrics and thus produce a multiple bottom
292 line. This reflects the fact that different categories of natural resources exist, and not all have
293 monetary values. Where monetary metrics are used, they are based on exchange values. The
294 outputs from accounts are designed for on-going management processes, thus allowing for

295 longitudinal analysis informing adaptive management. CBA is based on welfare values that
296 estimate utility and monetise all values that are aggregated to produce a single line answer²⁹.
297 Consumer surplus is included in the value, that is, the maximum amount that consumers
298 would have paid if required, but did not pay because producers were willing to sell at lower
299 prices, or it was provided for free, for example by governments. CBA seeks to monetize
300 potential changes in welfare brought about by different potential decisions at a single point in
301 time. The best decision is the one that achieves the greatest net change in welfare as
302 measured in monetary terms.

303 Ecosystem accounting presents a framework that can unify existing diverse data from
304 monitoring environmental and economic activities in any region. It provides a consistent
305 methodology for evaluating trade-offs between uses of ecosystem assets and their services. It
306 offers the capacity for a compelling foundation for decision-making about natural resource
307 management by presenting an integrated picture of benefits of ecosystems to society based on
308 metrics that matter to human well-being. Application of ecosystem accounts has major
309 implications globally for better recognising ecosystem services, identifying trade-offs to
310 improve ecosystem condition, and defining solutions to environmental-economic conflicts.

311 Challenges remain in designing, implementing and communicating the information in
312 ecosystem accounts. The accounts are in the form of a mix of physical and monetary metrics
313 because it is not yet possible to monetise the values of all ecosystem assets and services, as
314 we have described for biodiversity. Indeed, it may not be possible to attribute monetary
315 values fully, and the decision-making process will have to cope with a multiple bottom line
316 for assets and trade-offs in different units of measurement for services. The monetary metrics
317 used in accounts are transaction values to make them comparable with the SNA, however,
318 this means that potential improvements in welfare from the ecosystem services are not
319 included. Attempting to include the values for comprehensive ecosystem assets and services

320 within the decision-making process, even with the range of metrics, is an advance from the
321 current situation where most ecosystem values are not included.

322 Our novel approach to ecosystem accounts was the first time that values of ecosystem
323 services and their contribution to GDP have been compared across natural resource sectors,
324 and this has informed decision-making about the relative values of conflicting activities in the
325 region. The imperative is to include the contribution of ecosystem services to human well-
326 being in policy-development and decision-making before they are lost through degradation
327 and depletion. In this way, the success of human enterprise can be directed to a more
328 sustainable trajectory, rather than one solely dependent on economic growth.

329

330 Methods

331 Study region

332 The Central Highlands region in Victoria is approximately 100 km north-east of Melbourne.
333 The region is 735,655 ha in area and consists predominantly of native forest on public land,
334 with about half currently managed for wood production and half for conservation. Public land
335 in Australia used for commercial native timber production is managed under Federal – State
336 government agreements³³. These agreements, reached through protracted and controversial
337 processes involving debates among public, industry, government and non-government
338 organisations, will expire within two years. Hence, improved decision-making processes are
339 imperative. The issue of specific concern in the Central Highlands is a proposal to expand
340 protected areas for conservation of endangered species, particularly the critically endangered
341 Leadbeater’s Possum, and for recreational amenity.

342 Physical supply of ecosystem services

343 The region provides ecosystem services both within the study area, and surrounding rural
344 areas and the city. These ecosystem services were quantified in terms of physical metrics of
345 stocks and stock changes. Native forest harvesting provides timber and paper products and
346 employment; regional employment is a key social, economic and political factor. The
347 forested catchments provide the main urban water supply for Melbourne and rural water
348 supply for agricultural areas, which are becoming increasingly threatened by droughts³⁴. The
349 temperate, evergreen forests have a high carbon density and thus maximizing their carbon
350 storage is an important climate change mitigation activity³⁵. Tourism is an increasing source
351 of economic activity and employment in the region, particularly due to the proximity of

352 Melbourne³⁶. Part of the region is used for agricultural production and plantation forestry is
353 expanding³⁷.

354 **Water provisioning service.** The water provisioning service is described in physical terms
355 by the runoff or water yield from the catchments in the study area, which provide inflows to
356 the reservoirs operated by Melbourne Water. Water yield was calculated across the study area
357 and provided information about the spatial distribution across the landscape, and annual
358 changes in response to climate variability, land cover change, and disturbance history.

359 Water yield was estimated each year using a spatially-explicit continental water balance
360 model calculated monthly across the study area^{38,39} (see details in Supplementary Methods).
361 Calculation of water yield used the balance between rainfall and evapotranspiration, soil
362 water storage capacity, and vegetation cover. Although more detailed hydrological models
363 exist (for example^{40,41}), the advantage of using the model based on eMAST data is that it is
364 applicable nationally and the same method can be used for developing water accounts in any
365 region.

366 Water yield in the catchments is driven by precipitation and evaporation, but also influenced
367 by the condition of the vegetation, with the main factor being age of the forest.

368 Evapotranspiration depends on leaf area index and leaf conductance, which vary with forest
369 age and thereby determine the shape of the water yield response curve⁴². Forest age was
370 determined from the last stand-replacing disturbance event, which refers to high severity fire
371 or clearfell logging for montane ash forest and rainforest, and clearfell logging for mixed
372 species forest. The response of water yield to forest age was derived from a synthesis of
373 information from the literature^{40,41,42,43,44,45,46,47,48,49}. Change in water yield is estimated as a
374 proportion of the pre-disturbance amount (Supplementary Figure 1). An increase in water
375 yield occurs for the first 1 to 5 years after stand-replacing disturbance in all forest types. In

376 montane ash forest and rainforest, a decrease in water yield then occurs because the
377 regenerating forest with dense leaf growth results in high water use by transpiration. The
378 greatest reduction occurs between the ages of 13 to 49 years and peaking at 25 years.
379 Maximum reduction from a pre-disturbance 1939 regrowth forest is 29%, and from an old
380 growth forest is 48%. Water yield is not fully restored for at least 80 years if a forest is
381 regrowth at the time it is disturbed, and 200 years if a forest is old growth at the time it is
382 disturbed.

383 The water yield calculated from the water balance model was derived for a constant
384 vegetation condition, thus producing a baseline yield. This baseline yield was compared with
385 the yield when forest age, and the change in age, were taken into account. The difference in
386 water yield with and without disturbance events, disaggregated into fire and logging events,
387 allowed attribution of the change in water yield. This information was used to analyse the
388 change in water yield in the counterfactual case, where logging had not occurred in the
389 catchments. Details of calculations of the water yield function with forest age taken into
390 account are provided in the Supplementary Methods.

391 **Carbon stocks and stock changes.** Carbon stocks in biomass were estimated for the
392 following components: above- and below-ground biomass, and living and dead biomass,
393 (insufficient data exist to estimate soil carbon spatially and temporally). A model of biomass
394 carbon stock estimated spatially across the landscape was derived for montane ash forests in
395 eastern Victoria, using spatial biophysical data and calibrated with site data (n = 930 sites) of
396 biomass carbon stocks calculated from tree measurements⁴⁹. Carbon stocks were derived in
397 relation to the environmental conditions at the site, forest type, age of the forest since last
398 stand-replacing disturbance event, and previous disturbance history of logging and fire.
399 Modelled carbon stocks were restricted to within the range of the calibration site data. For the
400 carbon accounts in the current study within a defined regional boundary, additional carbon

401 data were included for all land cover types within the study area to derive a base carbon stock
402 map. Carbon stocks were calculated for each grid cell related to spatial variation in
403 environmental conditions and based on the matrix of land cover types, forest age, and
404 disturbance history (Supplementary Methods and Supplementary Table 1).

405 Change in carbon stock over time was calculated from the base carbon stock map for the land
406 cover condition pre-2009 fire, and then using forward projections from 2009 to 2015, and
407 backwards projections from 2009 to 1990. Changes in carbon stocks resulted from: growth of
408 trees, emissions due to fire, collapse of dead standing trees, decomposition of dead biomass,
409 and losses due to logging. Functions describing these processes are provided in the
410 Supplementary Methods. The net carbon stock change is the balance between additions due
411 to growth and reductions due to combustion, decomposition and removal of stocks from the
412 site.

413 **Native forest timber provisioning.** Data about wood resources harvested from native forests
414 were sourced from the government agency responsible for managing the resource,
415 VicForests. Data included area harvested, wood yield, and wood volume for each forest type
416 and product type over time (1990 – 2014).

417 **Plantation timber provisioning.** Estimates of wood product volume and yield were derived
418 from a national carbon accounting model⁵¹, national data⁵², and data from the softwood
419 plantation company⁵³. Areas of hardwood and softwood plantations were derived from the
420 land use spatial data.

421 **Regulating services used in agricultural production.** The ecosystem services used for crop
422 production and fodder for livestock include pollination, abstraction of water, soil nutrient
423 uptake, and nitrogen fixation⁶. Some of these services would have been generated on the land
424 used for agricultural production (soil water and nutrient uptake), whereas others may have

425 been generated elsewhere (for example, pollination). For this account, all ecosystem services
426 produced (supplied) were allocated to the agricultural land cover.

427 **Cultural and recreational services.** The Central Highlands are used for various recreational
428 purposes. The region includes national parks and other reserves, as well as wineries and other
429 tourist attractions. As an example, visitation to national parks in the study area is
430 approximately three-quarters of a million in 2010-11⁵⁴.

431 **Habitat provisioning services.** One of the key services provided by native forests is nest
432 sites for animals and birds, which were measured using the number of hollow-bearing trees
433 (HBTs) per hectare^{26,55}. Numbers of arboreal marsupial animals, including the critically
434 endangered Leadbeater's Possum, and HBTs were monitored at 161 sites of different age
435 classes of regenerating forest after logging and old growth forest, over a 28-year period.
436 Several biodiversity metrics were compiled into accounts, including the total number of
437 species; lists of threatened species, the change in listed species over time and their threat
438 category; abundance and species diversity of arboreal marsupials and HBTs in a range of
439 forest age classes.

440 [Valuation of ecosystem services](#)

441 Where appropriate, the physical metrics of ecosystem services were converted to a value in
442 monetary terms as the physical quantity multiplied by the price. Valuation of ecosystem
443 services is complex because they are generally not exchanged within markets like other
444 goods and services. Therefore, economic principles must be applied to estimate the 'missing
445 prices' or prices that are implicitly embedded in values of marketed goods and services⁶.
446 Approaches to monetary valuation of ecosystem services depend on the type of ecosystem
447 service and the data available, and a range of methods were applied in the Central Highlands:

448 **Water provisioning service.** The value is equal to the volume of water inflows multiplied by
449 the price per unit of the service. The cost of the ecosystem service was estimated from the
450 replacement value of an alternative source if water was not available from the catchments⁵⁶.
451 This method assumes that (i) if the service was lost it would be replaced by users, and (ii)
452 users would not change their pattern of use in response to a price increase.

453 The resource rent approach could not be used for water because data were not available for
454 the value of water supply infrastructure and the associated costs of supply. Information about
455 the costs of water supply is not separated from the costs of sewerage. In addition, the price of
456 water is regulated by the Essential Services Commission⁵⁷, and hence the seller's price is
457 constrained. The production function approach to valuation also was rejected for this study
458 because of lack of data, which would require detailed information about prices paid by water
459 retailers and subsequent water consumers, as well as the value of all other inputs to the
460 productive activities of the businesses.

461 Calculation of the water provisioning service as a replacement cost is a method to estimate
462 price per unit of water. This method does not assume, however, that complete replacement is
463 a viable option for water provisioning. Transfer of water from another region would not
464 provide sufficient supply to meet the demand from Melbourne and would impact water
465 supply in the other region. The existing desalination plant at Wonthaggi does not have the
466 capacity to meet the total demand, and other impacts of constructing and operating the plant,
467 such as energy demand and greenhouse gas emissions, are not taken into account. Use of
468 recycled water would not provide sufficient quantity of a product of the same quality, and the
469 process would require high energy inputs.

470 **Carbon sequestration.** Positive net change in carbon stocks represent the ecosystem service
471 of carbon sequestration because carbon dioxide is removed from the atmosphere and stored in

472 a terrestrial ecosystem. Negative net change in carbon stocks, or emissions, represent a
473 contribution of the land use activity to the national greenhouse gas emissions. A market-
474 based system to offset negative environmental impacts of greenhouse gas emissions used the
475 net amount of carbon sequestered each year⁵⁸. A potential valuation was applied based on the
476 current Australian government market price for abatement of carbon dioxide (CO₂)
477 emissions. The time series for carbon sequestration reflects changes in carbon stocks, but the
478 price is based on the November 2015 auction value of \$A12.25 / tCO_{2_e}⁵⁸, which was
479 adjusted for inflation, but did not include potential changes in the price.

480 The trade-off in carbon sequestration, analysed for the counterfactual case where harvesting
481 ceased, was continued carbon stock gain as forest age increased, according to the forest
482 growth functions. The difference in net change in carbon stock density between the area
483 logged and the area unlogged but available for logging indicated the carbon sequestration
484 potential.

485 **Native forest timber provisioning service.** A market price was calculated as the volume of
486 timber harvested each year and the reported stumpage value, that is, the revenue from log
487 sales less harvesting and haulage costs⁵⁹. The area and volume harvested in the study area
488 were used to calculate the percentage of the state total contributed by the study area, which
489 was then applied to the state financial data.

490 **Plantation timber provisioning service.** Data for the gross value of hardwood and softwood
491 products⁵² were used for the State of Victoria, and scaled to the study area based on the ratio
492 of areas of each type of plantation within the study area and state. A value was derived for the
493 use of ecosystem services in the production of plantation timber, because the plantation is
494 within the production boundary of the market¹⁸. Unit resource rent was calculated from
495 Australian industry production data for the subdivision of forestry and logging, based on the

496 gross operating surplus and mixed income, consumption of fixed capital and return on fixed
497 capital⁶⁰. Resource rent as a percent of gross operating surplus was multiplied by IVA to
498 estimate the value of the ecosystem services contributing to production.

499 **Regulating services used in agricultural production.** The resource rent method⁶¹ was used
500 to value the regulating services used in agricultural production. Data on the volume, value
501 and costs of production for agriculture were available for statistical areas, the state, and
502 nationally, respectively^{61,63}. Each dataset was downscaled to the study area. This method has
503 been used by the ABS for similar accounting exercises. The unit resource rent is the
504 difference between the benefit price and the unit costs of labour, produced assets and
505 intermediate inputs⁶. These calculations assume that the percentage of the gross value of
506 agricultural production from the Central Highlands compared to Victoria, and the costs of
507 production compared nationally, are appropriate scalars. Additionally, the level of resource
508 rent generated from the Central Highlands is similar to the rest of Australia. These
509 assumptions are not likely to be accurate but are probably broadly indicative of the level of
510 services provided.

511 **Cultural and recreational services.** The use of these services by people can be valued as
512 part of the value to the area of the consumption by tourists. This consumption relies not just
513 on the ecosystem services, but also capital, labour and other inputs from the industries
514 supporting tourists, for example, restaurants and accommodation. The State of Victoria has
515 produced regional tourism satellite accounts⁶⁴. Values for the Central Highlands study area
516 were estimated by applying the fraction of area of the tourism regions within the study area to
517 the data in the tourism accounts. The cultural and recreational ecosystem services were
518 estimated using the resource rent approach, using coefficients of resource rent to total output
519 that are used by the ABS⁶⁵.

520 Valuation of industries

521 The key principle of valuation of economic activity is the exchange value, which is used
522 when transactions are valued at the price at which they were exchanged. Total value is the
523 price times the quantity sold, where the price usually represents the production cost plus a
524 profit to the producer. An exchange value is distinct from the notion of value used in welfare
525 economics, which is associated with utility and includes a consumer surplus.

526 For ecosystem services that are included in the market system, Industry Value Added (IVA)
527 is a standard metric used to quantify economic activity of industries and represents their
528 contribution to GDP, that is, IVA is part of the system of national accounts⁶⁶. The IVA metric
529 is calculated as the revenue from sales less costs, or the wages and profit before tax and fixed
530 capital consumption. IVA is derived for industries that produce goods and services that are
531 traded within the economy. In this study, these industries included native forest and
532 plantation timber, water, agricultural commodities, and the goods and services associated
533 with tourism. This economic information is recorded in publications by the ABS and in
534 annual reports of government agencies^{59,67}.

535 **Water supply.** Water supplied from the reservoirs to consumers within the economy was
536 valued as the revenue earned by Melbourne Water. Water supply includes drinking water,
537 environmental releases, irrigation entitlements, and extra allocations. Data is reported by
538 Melbourne Water⁶⁷ for the volume of water supplied, the revenue received from this supply,
539 and the costs of producing the water (wages and salaries, consumption of fixed capital and
540 other running costs, for example for reservoirs, water mains, pumps, etc.). These data were
541 used to generate an estimate of the IVA for water supply.

542 **Carbon sequestration.** There is no exchange value for carbon sequestration in native forests
543 because forest protection is not an approved abatement activity under the Australian

544 Government regulations⁶⁸. However, carbon is sequestered by forests and this benefits the
545 public through climate change mitigation, and through the state and national emissions
546 reduction targets. Hence, a value of carbon sequestration can be estimated if market access
547 was permitted under the Emissions Reduction Fund⁶⁸. Based on SNA approaches to valuation
548 when market prices are not observable, the SEEA⁶ uses a market price equivalent, which is
549 usually based on the market price of similar goods or services. In the case of carbon
550 sequestration, the price of carbon abatement is set by government auction irrespective of the
551 activity or methodology for abatement⁵⁸. This carbon price is equivalent to the revenue from
552 production. The IVA is estimated from revenue from carbon sequestration less costs of
553 managing the forest. Managing the forest for carbon storage was assumed similar to that for a
554 national park, and costs were estimated from the financial accounts of Parks Victoria⁷⁰

555 **Native timber supply.** The revenue from native timber supply is reported by VicForests⁵⁹.
556 IVA was calculated as the sum of wages, employee benefits, depreciation, amortisation and
557 net operating result before tax.

558 **Plantation timber supply.** IVA was calculated from the total industry output for hardwood
559 and softwood plantations less the intermediate consumption⁶⁰, scaled to the study area.

560 **Agricultural production.** IVA was calculated from the total industry output for agricultural
561 production less the intermediate consumption⁶¹, scaled to the study area.

562 **Tourism.** The regional tourism satellite accounts⁶⁴ provided data for IVA and this was scaled
563 to the study area.

564 [Spatial distribution of ecosystem services](#)

565 Spatial distributions of ecosystem services were derived from their physical metrics in
566 relation to land cover, land use and the environmental conditions across the landscape. They

567 were calculated for water provisioning (Supplementary Figure 2), carbon storage
568 (Supplementary Figure 3) and native timber provisioning (Supplementary Figure 4).

569 The value of the timber provisioning service was derived from the forest age weighted by
570 forest type. Forest age was calculated from the last regeneration event and range-normalised
571 to an index between 0 and 1. The forest age index was multiplied by a weighting for forest
572 type (ash = 1; wet, mixed species = 0.667; open, mixed species = 0.333). The physical
573 metrics for carbon storage (tC ha^{-1}) and water yield (ML yr^{-1}) are continuous variables that
574 were range-normalised to indices between 0 and 1. The interaction of the values of ecosystem
575 services was derived from the product of these three component indices. This interaction
576 index showed the areas of relatively highest value or ‘hotspots’.

577 The indices are continuous from 0 to 1, but are displayed on the map (Figure 5) as 5 classes
578 for ease of comparison. Classification used the Jenks natural breaks optimization function in
579 ARC GIS. This is a data clustering method designed to reduce the variance within classes and
580 maximise the variance between classes. Because the data are highly skewed, this
581 classification produced more even classes than using equal class sizes.

582 **Data Availability.** The data that support the findings of this study are available in the
583 Supplementary Methods and in a full report from <http://www.nespthreatenedspecies.edu.au/>

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771

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783

784 **Author contributions:** Study designed by HK, MV and DL; calculations performed by HK
785 and MV; spatial analysis by JAS; hydrological modelling by JLS; manuscript written by HK
786 and contributed to by MV and DL.

787 **Competing interests:** All authors declare no competing financial interests.

788

789 Figure legends

790 **Figure 1. The environmental-economic system showing the stocks and flows of natural** 791 **resources**

792 Ecosystem assets are identified and their physical state measured in a spatially explicit
793 manner in terms of extent and condition, their ownership, and management (individuals,
794 industries or government). Thus, ecosystems are linked directly to uses by people. The uses
795 of these ecosystem assets by human activities are the ecosystem services. Ecosystem services
796 are combined with human inputs, such as capital and labour, in the production of goods and
797 services, which produce benefits when used by people. Different sectors of society are the
798 beneficiaries of these products. Production of goods and services can impact other ecosystem
799 assets, and these trade-offs can be assessed. Components of the system are quantified using
800 physical or monetary metrics. Only parts of the system (indicated by the dashed line) are
801 included in the calculation of Gross Domestic Product (GDP), which accounts for flows of
802 market goods and services, such as agricultural products, timber products, water supply,
803 tourism and recreational services. Non-market goods and services that are not accounted for
804 in GDP include clean air, protection from flooding and soil erosion, biodiversity, aesthetic
805 benefits and climate change mitigation. The boundary of contributions of ecosystem services
806 to markets or non-markets is difficult to define (that is, the position of the dashed line).

807 Activities are assessed at balance points where components of the system are reasonably
808 comparable: the use of ecosystem services can be complementary or conflicting; trade-offs
809 resulting from the relative impacts or benefits of producing goods and services; and who
810 benefits within human society.

811

812 **Figure 2. Landscape context of ecosystem assets and services.**

813 Ecosystem accounting describes interactions of living organisms and components of the
814 environment within specific geographical areas. Ecosystem assets and the services they
815 provide to support human well-being are located spatially across the landscape.

816 **Figure 3. Value of (a) ecosystem services, and (b) Industry Value Added generated in**
817 **the Central Highlands.**

818 (a) The monetary value of ecosystem services when used by industries or households, is
819 expressed as changes over time that reflect the changes in stocks and price. Water
820 provisioning was the most valuable ecosystem service from the study area, but since 2014,
821 the regulating ecosystem services used in agricultural production have been greater. The
822 trend in carbon sequestration reflects only changes in net carbon stocks because a constant
823 carbon price, adjusted for inflation, was applied. Decreases in carbon sequestration occurred
824 after fires in 2007 and 2009 due to emissions from combustion, but then increased in the
825 following years.

826 (b) Contributions of industries to the economy, based on the metric of IVA, show that
827 agriculture, water supply and tourism are an order of magnitude above that of native forestry.
828 IVA for plantation forestry is greater than that for native forestry, even though the area of
829 land managed for plantations is 14% of the area of native forest available for harvest. The
830 decrease in IVA for water supply from 2012 to 2013 was due to the expenses associated with
831 constructing a desalination plant. Revenue increased in the following two years due to a
832 higher price for water. The IVA for tourism has increased since 2012, mainly due to
833 increased numbers of international visitors, aided by the declining exchange rate post the
834 global financial crisis and mining boom.

835

836 **Figure 4. Value of ecosystem services and Industry Value Added (2013-14), and the**
837 **potential changes if native forest harvesting ceased**

838 Trade-offs in values of ecosystem services and IVA were derived from analyses of the
839 counterfactual case; the difference in values of services if harvesting had **not** occurred. This
840 analysis allows comparison of the losses from ceasing native forest timber harvesting with
841 the gains in other ecosystem services if forest growth continued leading to greater forest age.
842 Gains in carbon sequestration and water yield were quantified and considered as known
843 gains. Gains in cultural and recreational services and plantation timber provisioning were
844 estimated from information in the literature, with a low and high range, and considered as
845 potential gains.

846 **Figure 5. Spatial distribution of the Interaction Index of ecosystem service values.**

847 The index combines values for water provisioning, native timber provisioning and carbon
848 storage. Areas of highest values in red identify the ‘hotspots’, where maximum provisioning
849 for native timber conflicts with maximising services of water provisioning and carbon
850 storage.

851 (a) All forest land in the study area

852 (b) Forest area with land management tenure available for logging

853

854 Table 1

855 **Comparison of the current benefits, in physical and monetary terms, from native timber**
856 **production with the gain in benefits from carbon sequestration, water yield and habitat**
857 **provisioning if harvesting had not occurred and the forest had continued growing**

	Physical metric	Ecosystem service	Industry Value Added
		(\$Amillion yr⁻¹)	(\$Amillion yr⁻¹)
Native timber production	0.724 Mm ³ yr ⁻¹	18.7	12.2
Carbon sequestration	0.344 Mt C yr ⁻¹	15.5	12.6
Water yield	10.5 GL yr ⁻¹	2.5	8.1
Habitat provisioning	8.5 HBTs ha ⁻¹		

858 Analysis based on the area that has been harvested and values in 2013-14.

859 HBTs hollow-bearing trees

860