

## POLICY FORUM

## ECONOMICS AND THE ENVIRONMENT

# Progress in natural capital accounting for ecosystems

Global statistical standards are being developed

By **Lars Hein, Kenneth J. Bagstad, Carl Obst, Bram Edens, Sjoerd Schenau, Gem Castillo, Francois Soulard, Claire Brown, Amanda Driver, Michael Bordt, Anton Steurer, Rocky Harris, Alejandro Caparrós**

Reversing the ongoing degradation of the planet's ecosystems requires timely and detailed monitoring of ecosystem change and uses. Yet, the System of National Accounts (SNA), first developed in response to the economic crisis of the 1930s and used by statistical offices worldwide to record economic activity (for example, production, consumption, and asset accumulation), does not make explicit either inputs from the environment to the economy or the cost of environmental degradation (1, 2). Experimental Ecosystem Accounting (EEA), part of the System of Environmental-Economic Accounting (SEEA), has been developed to monitor and report on ecosystem change and use, using the same accounting approach, concepts, and classifications as the SNA (3). The EEA is part of the statistical community's response to move SNA measurement "beyond gross domestic product (GDP)." With the first generation of ecosystem accounts now published in 24 countries, and with a push to finalize a United Nations (UN) statistical standard for ecosystem accounting by 2021, we highlight key advances, challenges, and opportunities.

## PROGRESS TO DATE

Led by the UN Statistical Commission (UNSC) and involving statistical offices from all continents, international organizations such as the European Commission and the World Bank, and several hundred scientists and nongovernmental organization representatives, the SEEA is the world's leading natural capital accounting approach. The SEEA includes two parts: the Central Framework (CF), adopted as a statistical standard by the UNSC in 2012 (4), and the EEA framework (not yet a standard), first published in 2014 (5). In an accounting sense, the CF extends the asset

boundary of the SNA (in physical, not monetary, terms), whereas the EEA also extends the production and consumption boundary. The CF measures emissions, stocks and uses of individual natural resources, and transactions related to environmental management. The CF is used, in particular, to report on water; energy, including oil and natural gas reserves; mineral ores; and emissions to air. The EEA provides a framework for measuring ecosystems and their uses and recognizes that ecosystems generate multiple types of services (provisioning, regulating, and cultural). By broadening measures of production, consumption, income, and asset value, ecosystems' contributions to society become visible. Furthermore, in recognition of the spatial heterogeneity of ecosystems, the EEA uses maps for analytical and reporting purposes. The EEA includes individual accounts recording: the extent of different ecosystem types, their condition, physical and monetary flows of ecosystem services, and the monetary value of ecosystem assets. Additionally, the EEA includes thematic accounts for land, water, carbon, and biodiversity (6). Countries typically compile the most policy-relevant accounts first. Because of their spatial nature, the EEA can report by ecosystem types, watersheds, or administrative units.

To maintain consistency with the SNA, monetary valuation in the SEEA is based on exchange prices—prices at which goods, services, or assets are or could be transacted. Monetary values in the SEEA thus complement those provided in the SNA and can be used to analyze the contribution of natural capital to the economy or compare the costs of ecosystem degradation with increases in economic output, among others.

EEA accounts have now been published in 24 countries [see the figure and supplementary materials (SM), section 1]. The United Kingdom (7) and the Netherlands (8) have published the most comprehensive accounts to date. Both countries' accounts include detailed maps and physical and monetary accounting tables. In Australia, several accounts have been published at the national and local scale (9). In Andalusia (Spain), ecosystem service accounts have

been compiled and environmental income assessed (10). In South Africa, national ecosystem accounts have been developed for the extent and condition of rivers (11). Supranational accounts have been developed for the European Union (12). In Organisation for Economic Co-operation and Development (OECD) countries, national governments financed the compilation of accounts, whereas in many developing countries, donors have contributed, either directly or through UN or World Bank programs. Statistical agencies differ in their capacity to analyze ecosystems and their services and have often collaborated with specialized research institutes and universities.

## POLICY APPLICATIONS

A key feature of the accounts is to show ecosystems' contributions to the economy. For example, the contributions of nature recreation and tourism and crop provisioning services to the economy are relatively high in the United Kingdom and the Netherlands (7, 8). This reflects both the relative contribution of ecosystems to the tourism sector and agriculture and the economic importance of these activities. Per-hectare monetary values are around 50% higher in the Netherlands. This is mainly due to broader coverage for the service "recreation and tourism."

EEA accounts can inform various natural resource management decisions (13). In the Netherlands, for example, EEA accounts show that in peat areas used for dairy farming, the combined costs of maintaining infrastructure and controlling water levels and carbon dioxide emissions considerably exceed farmers' profits. This has led to new policies aimed at reducing drainage in peatlands and converting farmland back to natural ecosystems (14). In Indonesia, local governments have responsibility for land-use planning but often lack spatial information on forest extent, condition, and use. Accounts can facilitate local government efforts to plan, implement, monitor, and enforce forest management policies, provided that statistical offices make high-resolution spatial data available.

The accounts can enhance transparency and fairness of ecosystem use. For example, information is often lacking on rents resulting from the exploitation of ecosystems (for example, for timber extraction or plantation agriculture). EEA accounts show these rents in a spatially explicit manner, providing an objective basis for their taxation. The EEA also allows trends in ecosystem extent, condition, and use to be monitored, including UN Sustainable Development Goals indicators. The EEA accounts can provide comprehensive and objective baseline data

See supplementary materials for author affiliations.  
Email: lars.hein@wur.nl

## Countries that have compiled SEEA EEA accounts

Some countries have published all accounts that they have compiled, and others have published only some. China, Japan, and the United States have compiled accounts but not published them (see supplementary materials, section 1). The scope and resolution of the accounts vary between countries. The figure presents a snapshot—countries continue to compile and publish accounts. SEEA, System of Environmental-Economic Accounting; EEA, Experimental Ecosystem Accounting.



for private-sector natural capital accounting, for example, with the Natural Capital Protocol. This allows businesses to better understand their impacts and dependency on natural capital.

### CHALLENGES AND OPPORTUNITIES

Ecosystem accounts published to date vary in scope and level of (spatial) detail. This reflects differences in budget, technical capacity, and data between countries, with notable constraints in developing countries. Compiling the full suite of ecosystem accounts requires substantial data and use of multiple biophysical models (see SM, section 2). The Netherlands ecosystem accounts provide 90 policy-relevant indicators, derived from various datasets and models. They indicate, for example, how small landscape elements such as hedgerows contribute to crop production by maintaining pollinator populations.

Institutional challenges occur, for instance, in relation to integrating data from different agencies: Data may be in incompatible formats, or there may be a reluctance to share it. Furthermore, the SEEA has a different measurement approach compared with some existing reporting systems (for example, carbon reporting under the UN Framework Convention on Climate Change). Collaboration between government institutes holding different datasets facilitates enhanced data integration and greater commonality in terminology and definitions (13).

Some technical challenges remain. For instance, the diversity of ecosystems makes

selection of ecosystem condition and biodiversity indicators challenging. In South African and Australian accounts, ecosystem condition has been defined in relation to pre-European settlement conditions, which is not useful for western Europe with its long ecosystem-use history. Challenges also exist in valuing nonmarket ecosystem services such as water regulation and air filtration.

The EEAs inherent limitations should be considered when the accounts are used in policy-making. The EEA accounts produced to date do not include indicators for ecosystem resilience or consider probabilities of sudden future collapses of overexploited ecosystems (15). Furthermore, exchange prices of ecosystem services reflect current pricing mechanisms and market conditions. Given that the SEEA does not record the welfare generated by using natural capital (2), it is imperative that monetary values in the EEA are not interpreted as representing “the value of nature” (see SM, section 3).

Several ongoing efforts address remaining challenges to the global implementation of the EEA. The UNSC is working with scientists and statisticians toward establishing a statistical standard for the EEA by 2021. Working groups have been established to address remaining technical issues, including defining metrics expressing ecosystem condition, biodiversity, and the capacity of ecosystems to supply services and valuing nonmarket ecosystem services (for instance, on the basis of simulated exchange values). Through various scientific efforts connected

to the EEA, such as the Earth Observation for Ecosystem Accounting initiative of the Group on Earth Observations, tests are being done to examine how ecosystem extent, condition, and regulating services can be modeled across large countries or even continents at high resolution using data from remote-sensing and global datasets. Increasingly, machine-learning techniques are used, for instance, to assess the impacts of ecosystem changes on hydrological cycles and the availability of water for people. Social media posts can be used to analyze recreation in ecosystems, for example. The EEA is making large datasets available to a variety of users, and global, high-resolution modeling of critical ecosystem characteristics and services will facilitate easier uptake of the EEA in developing countries.

The EEA allows consistent (over time and between countries), comprehensive, and high-resolution analysis and reporting on ecosystems and their use. The EEA accounts do not capture all connections between people and nature and have limited capacity to consider ecosystem complexities such as thresholds and feedbacks. These caveats need to be clearly articulated when EEA accounts are published. Nonetheless, the EEA considerably enhances the scope and accuracy of information available in support of ecosystem management, facilitating better management of global natural capital. ■

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### SUPPLEMENTARY MATERIALS

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## Supplementary Materials for **Progress in natural capital accounting for ecosystems**

Lars Hein\*, Kenneth J. Bagstad, Carl Obst, Bram Edens, Sjoerd Schenau, Gem Castillo,  
Francois Soulard, Claire Brown, Amanda Driver, Michael Bordt, Anton Steurer,  
Rocky Harris, Alejandro Caparrós

\*Corresponding author. Email: [lars.hein@wur.nl](mailto:lars.hein@wur.nl)

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List of author affiliations  
Supplementary Text  
References

## Author affiliations

Lars Hein<sup>1</sup>, Kenneth J. Bagstad<sup>2</sup>, Carl Obst<sup>3</sup>, Bram Edens<sup>4</sup>, Sjoerd Schenau<sup>5</sup>, Gem Castillo<sup>6</sup>, Francois Soulard<sup>7</sup>, Claire Brown<sup>8</sup>, Amanda Driver<sup>9</sup>, Michael Bordt<sup>10</sup>, Anton Steurer<sup>11</sup>, Rocky Harris<sup>12</sup>, Alejandro Caparrós<sup>13</sup>

<sup>1</sup>Wageningen University and Research, Wageningen, Netherlands.

<sup>2</sup>Geosciences & Environmental Change Science Center, U.S. Geological Survey, Denver, CO, USA.

<sup>3</sup>Institute for Development of Environmental-Economic Accounting and University of Melbourne, Melbourne, Australia.

<sup>4</sup>UN Statistics Division, New York, NY, USA.

<sup>5</sup>Statistics Netherlands, The Hague, Netherlands.

<sup>6</sup>Resources, Environment and Economics Center for Studies, Philippines.

<sup>7</sup>Environmental Accounts and Statistics Program, Statistics Canada, Ottawa, Ontario, Canada.

<sup>8</sup>UN Environment World Conservation Monitoring Centre, Cambridge, UK.

<sup>9</sup>South African National Biodiversity Institute, Pretoria, South Africa.

<sup>10</sup>United Nations, Economic and Social Commission for Asia and the Pacific, Bangkok, Thailand.

<sup>11</sup>Statistical Office of the European Union, Luxembourg.

<sup>12</sup>Department for Environment, Food and Rural Affairs, London, UK.

<sup>13</sup>Spanish National Research Council (CSIC), Institute for Public Goods and Policies, Madrid, Spain.

## Supplementary material #1

### The state of ecosystem accounting by country

The table was prepared based on a review of the literature and websites of statistical offices world-wide, and also draws upon the experience of the authors, who have all been involved in the preparation of SEEA EEA accounts in their respective countries or regions, and as advisors to the compilation of SEEA EEA accounts in other countries. It reflects current knowledge as of December 2019.

Note 1: Land and water accounts are part of both the SEEA Central Framework and SEEA EEA. Accounts count as publications under SEEA EEA if they are explicit in their reports that accounts are produced under SEEA EEA and follow SEEA EEA conventions (implying a spatial approach to analyzing ecosystem assets). Several countries, such as Botswana and Brazil, have published a water account following the Central Framework, i.e., without spatial analysis or reference to the SEEA EEA. In these cases, these accounts have not been included in the table below.

Note 2: The European Union has published extent, monetary and physical ecosystem services, land, water and biodiversity accounts for the whole of the EU , and the European Environment Agency, the Joint Research Centre and Eurostat are continuously enhancing and expanding the SEEA EEA accounts. The table below presents national-scale efforts only.

Note 3: Several EU countries started preparation of SEEA EEA accounts in early 2019, in the context of the EU Horizon2020 'MAIA: project (Mapping and Assessment for Integrated ecosystem Accounting; <http://www.ecosystemaccounts.org/home/maia.jsp>). These include Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Greece, Norway, the Netherlands and Spain. Of these, the Finland, the Netherlands, Norway and Spain have published SEEA EEA accounts already and are included in the table. In the remaining countries, SEEA EEA work has started with the selection of accounts to be compiled (as per December 2019). These countries are not included in the table below.

Note 4: Nepal and Myanmar recently started the compilation of forest accounts, and China, Malaysia, Samoa, Thailand and Vietnam have started compiling ocean accounts following the SEEA EEA. These activities were also started recently and are not yet included in the table below.

Table S1. The state of ecosystem accounting by country

Key: 1 = national, 2 = sub-national, a=published, b=compiled but not yet published

Country	Main institutions involved	Extent account	Condition account	Biophysical ecosystem services account	Monetary ecosystem services account	Ecosystem asset account	Carbon account	Land account	Water account	Biodiversity account	References
Australia	Australian Bureau of Statistics, State government agencies, Australian National University	2a	2a	2a	2a		1a	2a	1a	2a	<p>Ajani J. and Comisari P. Towards a comprehensive and fully integrated stock and flow framework for carbon accounting in Australia', Australian National University, Canberra (2014)</p> <p>Australian Bureau of Statistics. Experimental Environmental-Economic Accounts for the Great Barrier Reef (2017)</p> <p>Department of Sustainability and Environment. Victorian Experimental Ecosystem Accounts. (2013)</p> <p><a href="https://unstats.un.org/unsd/envaccounting/londongroup/meeting19/LG19_16_5.pdf">https://unstats.un.org/unsd/envaccounting/londongroup/meeting19/LG19_16_5.pdf</a></p> <p>Keith H, Vardon M, Stein JA, Stein JL, Lindenmayer D. Ecosystem accounts define explicit and spatial trade-offs for managing natural resources. Nat Ecol Evol 1: 1683–1692. (2017)</p> <p>Parks Victoria. Valuing Victoria's Parks (2015)</p> <p><a href="https://www.worldurbanparks.org/images/Documents/Valuing-Victorias-Parks-Report-Accounting-for-ecosystems.pdf">https://www.worldurbanparks.org/images/Documents/Valuing-Victorias-Parks-Report-Accounting-for-ecosystems.pdf</a></p> <p>Wentworth Group of Concerned Scientists. Accounting for nature (2016)</p> <p><a href="https://wentworthgroup.org/2016/12/accounting-for-nature-2016/2016/">https://wentworthgroup.org/2016/12/accounting-for-nature-2016/2016/</a></p>

Canada	Statistics Canada	1a						1a	1a	<p>Statistics Canada. The changing landscape of census metropolitan areas. Human Activity and the Environment, Catalogue no. 16- 201-X, (2016)</p> <p><a href="https://www150.statcan.gc.ca/n1/pub/16-201-x/16-201-x2016000-eng.htm">https://www150.statcan.gc.ca/n1/pub/16-201-x/16-201-x2016000-eng.htm</a></p> <p>Statistics Canada. Freshwater in Canada. Human Activity and the Environment, Catalogue no. 16-201-X, (2017).</p> <p><a href="https://www150.statcan.gc.ca/n1/pub/16-201-x/16-201-x2017000-eng.pdf">https://www150.statcan.gc.ca/n1/pub/16-201-x/16-201-x2017000-eng.pdf</a></p> <p>Statistics Canada. Forests in Canada,” Human Activity and the Environment, Catalogue no. 16-201-X (2018)</p>
China	National Bureau of Statistics, regional government, Chinese Academy of Sciences	2b	2b	2b	2b					<p>National Bureau of Statistics, China. Natural Capital Accounting and Valuation of Ecosystem Services (2019).</p> <p><a href="https://seea.un.org/content/natural-capital-accounting-and-valuation-ecosystem-services-china">https://seea.un.org/content/natural-capital-accounting-and-valuation-ecosystem-services-china</a></p>
Colombia	Institute of Hydrology, Meteorology and Environmental Studies; The Department of National Planning			2a	2a			1a	1a	<p>World Bank. Natural Capital Accounting and Policy Colombia, Policy brief, WAVES (2017)</p> <p><a href="https://www.wavespartnership.org/en/knowledge-center/natural-capital-accounting-and-policy-colombia">https://www.wavespartnership.org/en/knowledge-center/natural-capital-accounting-and-policy-colombia</a></p>
Costa Rica	Central Bank	1a		1a					1a	<p>Banco Central de Costa Rica. Cuentas Ambientales de Costa Rica (2018)</p> <p><a href="https://seea.un.org/sites/seea.un.org/files/costa_rica_cuentas_ecosistemas.pdf">https://seea.un.org/sites/seea.un.org/files/costa_rica_cuentas_ecosistemas.pdf</a></p> <p><a href="http://www.inec.go.cr/medio-ambiente/indicadores-ambientales">http://www.inec.go.cr/medio-ambiente/indicadores-ambientales</a></p>



Croatia	Energy Research Institute, Agency for Environment and Nature	1a		2a						Energy Research Institute. Final report about the assessment of the selected ecosystem service with detailed methodology explanation. Energy Research Institute, Zagreb (2018) <a href="https://biodiversity.europa.eu/maes/maes_countries/croatia">https://biodiversity.europa.eu/maes/maes_countries/croatia</a>
Denmark	Statistics Denmark			1a				1a		Vind, I, 2018. Developing Ecosystem Services Accounts from Land Accounts. Final report Statistics Denmark (2018)
Finland	Finnish Environment Institute – SYKE	1b		2a	2b					Lai et al. Bridging the gap between ecosystem service indicators and ecosystem accounting in Finland. Ecological Modelling 377:51-65 (2018) Project information: <a href="https://www.syke.fi/projects/estat-eea">https://www.syke.fi/projects/estat-eea</a>
Guatemala	Central Bank, Institute of Research on Environment (a.o.)	1a	2a	2a	2a			2a		World Bank. Toward Natural Capital Accounting in Guatemala – Synthesis Report (2019) <a href="https://www.wavespartnership.org/sites/waves/files/kc/WAVES_Towards-Natural-Capital-Accounting-in-Guatemala-Synthesis-Report.pdf">https://www.wavespartnership.org/sites/waves/files/kc/WAVES_Towards-Natural-Capital-Accounting-in-Guatemala-Synthesis-Report.pdf</a>
India	National Statistical Office		1a		1a			1a		EnviStats India. Volume II – Environment Accounts, Ministry Of Statistics and Programme Implementation, National Statistics Division (2019) EnViStats Supplement on Environmental Accounts (2018)

Indonesia	Central Statistical Office (BPS), National Development Planning Agency	2a	2a	2a	2a			1b			Government of Indonesia, Badang Pusat statistics, in press. Land and extent account for Indonesia, Pilot peat ecosystem account. <a href="http://documents.worldbank.org/curated/en/280931564033874140/pdf/Pilot-ecosystem-account-for-Indonesian-peatlands-Sumatra-and-Kalimantan-islands.pdf">http://documents.worldbank.org/curated/en/280931564033874140/pdf/Pilot-ecosystem-account-for-Indonesian-peatlands-Sumatra-and-Kalimantan-islands.pdf</a>
Italy	National Capital Committee comprising representatives of (a.o.) 10 ministries	1a	1a	1a							Second Report on the State of Natural Capital in Italy, The Natural Capital Committee. <a href="https://www.minambiente.it/sites/default/files/archivio/allegati/sviluppo_sostenibile/II_Rapporto_Stato_CN_2018_3.pdf">https://www.minambiente.it/sites/default/files/archivio/allegati/sviluppo_sostenibile/II_Rapporto_Stato_CN_2018_3.pdf</a>
Japan	Policy Research Institute, Ministry of Agriculture, Forestry and Fisheries; Kobe University			1b				1b			Hayashi, T. and M. Sako. Ecosystem service valuation and ecosystem asset account in Japan (2019) <a href="https://seea.un.org/sites/seea.un.org/files/lg23_ecosystem_service_valuation_asset_accounts_japan.pdf">https://seea.un.org/sites/seea.un.org/files/lg23_ecosystem_service_valuation_asset_accounts_japan.pdf</a>
Liberia	Conservation International	1a		2a				1a		2a	Neugarten, R. M. Alam, M. Honzák, D. Juhn Natural Capital Mapping and Accounting in Liberia: Understanding the contribution of biodiversity and ecosystem services to Liberia's sustainable development. Technical Report Conservation International (2017)

Madagascar	Ministry of Economy and Industry			2a					1a		World Bank. Madagascar valuing ecosystem services in the CAZ forestry corridor. World Bank, Washington, DC, USA. (2012) <a href="https://www.wavespartnership.org/sites/waves/files/kc/A4-60pages-eau-9-PRINT%281%29.pdf">https://www.wavespartnership.org/sites/waves/files/kc/A4-60pages-eau-9-PRINT%281%29.pdf</a>
Mauritius	Indian Ocean Commission, Statistics Mauritius	1a	1a					1a	1a	1a	Weber, JL, 2014. Experimental ecosystems natural capital accounts; Mauritius case study. Indian Report Ocean Commission, Mauritius
Mexico	National Institute of Statistics and Geography (INEGI)	1b	1b	1b	1b			1a	1a	1a	INEGI website on environmental accounts: <a href="https://www.inegi.org.mx/temas/ee/default.html#Informacion_general">https://www.inegi.org.mx/temas/ee/default.html#Informacion_general</a> , <a href="https://www.inegi.org.mx/app/mapas/">https://www.inegi.org.mx/app/mapas/</a> <a href="https://seea.un.org/sites/seea.un.org/files/documents/Forum_2018/s13_mexico.pdf">https://seea.un.org/sites/seea.un.org/files/documents/Forum_2018/s13_mexico.pdf</a> INEGI. Technical note water accounts (2018) <a href="https://seea.un.org/sites/seea.un.org/files/8_9.pdf">https://seea.un.org/sites/seea.un.org/files/8_9.pdf</a> Schipper A., M. Tillmanns, P. Giesen, S van der Esch, 2017 Compiling biodiversity accounts with the GLOBIO model. A case study of Mexico Technical Note PBL, the Hague, the Netherlands (2017).
Netherlands	Statistics Netherlands, Wageningen University	1a	1a	1a	1a	1a	1a		1a	1b	Statistics Netherlands, 2017, 2018, 2019. SEEA EEA accounts for the Netherlands. <a href="https://www.cbs.nl/en-gb/society/nature-and-environment/natural-capital">https://www.cbs.nl/en-gb/society/nature-and-environment/natural-capital</a>

Norway	Statistics Norway, Norwegian Institute for Nature Research	2a		2a	2b	2b				2a	NINA. Urban ecosystem accounts for Oslo municipality (2019) <a href="http://urban.nina.no/">http://urban.nina.no/</a>
Peru	Regional Government of San Martin; Conservation International	2a	2a	2a	2a			2a		2a	Reporte técnico Gobierno Regional San Martín and Conservation International. Cuentas experimentales de los ecosistemas en San Martín, Perú (2016).
Philippines	Philippines Statistics Authority, Palawan Council for Sustainable Development, Laguna Lake Development Authority		2a	2a	2a		2a				Government of the Philippines, 2017. Pilot Ecosystem Account for Laguna de Bey; <a href="https://www.wavespartnership.org/sites/waves/files/kc/LdeBay%20FINAL%20LowRes%20Dec15%202016.pdf">https://www.wavespartnership.org/sites/waves/files/kc/LdeBay%20FINAL%20LowRes%20Dec15%202016.pdf</a> Government of the Philippines, 2017. Pilot Ecosystem account for Palawan. <a href="https://www.wavespartnership.org/sites/waves/files/kc/WB_Southern%20Palawan%20Tech%20Report_FINAL_Nov%202016.pdf">https://www.wavespartnership.org/sites/waves/files/kc/WB_Southern%20Palawan%20Tech%20Report_FINAL_Nov%202016.pdf</a>
Rwanda	Ministry of Natural Resources, Ministry of Finance and Economic Planning, National Institute of Statistics	1a		1b			1b	1a	1a		Government of Rwanda. Rwanda Natural Capital Accounts – Land (2018) Government of Rwanda. Rwanda Water Accounting Report 2012-2015 (2019) Mukarubibi, F. Rwanda Natural Capital Accounting. Ministry of Natural Resources, Rwanda (2015)

South Africa	South African National Biodiversity Institute, Statistics South Africa	2a,1b	1b	2b	2b			2a	1a	1b	Nel, J.L., A. Driver. National River Ecosystem Accounts for South Africa. Discussion document for Advancing SEEA Experimental Ecosystem Accounting Project. South African National Biodiversity Institute, Pretoria (2015) Statistics South Africa. Natural resource accounts: water accounts for nineteen water management areas. Government of South Africa (2000).
Spain	Spanish National Research Council, Regional Government of Andalusia	2a, 1b		2a	2a	2a			2a		Campos P. et al. Bridging the Gap Between National and Ecosystem Accounting Application in Andalusian Forests, Spain. Ecological Economics, 218-236 (2019). Caparrós, A., Oviedo, J.L., Álvarez, A. and Campos, P. Simulated Exchange Values and Ecosystem Accounting: Theory and Application to Free Access Recreation. Ecological Economics 139: 140–149 (2017). Gutiérrez-Martín, C., M.M. Borrego-Marín., and J. Berbel. The Economic Analysis of Water Use in the Water Framework Directive Based on the System of Environmental-Economic Accounting for Water: A Case Study of the Guadalquivir River Basin. Water 9:180 (2017) Pedro-Monzonis, M., A. Solera, J. Ferrer, J. Andreu, and T. Estrela. Water accounting for stressed river basins based on water resources management models. Science of the Total Environment 565:181-190 (2016)

Uganda	UNEP-WCMC									1a	UNEP-WCMC & IDEEA Technical report Experimental Ecosystem Accounts for Uganda. UN Environment World Conservation Monitoring Centre (UNEP-WCMC), Cambridge, UK (2017).
United Kingdom	Office of National Statistics, Department for Food, Environment and Rural Affairs	1a	1a	1a	1a	1a	1a	1a	1a		Office for National Statistics and Department for Environment, Food and Rural Affairs. UK Natural capital accounts (2019) <a href="https://www.ons.gov.uk/economy/environmentalaccounts">https://www.ons.gov.uk/economy/environmentalaccounts</a>
United States	U.S. Geological Survey, Bureau of Economic Analysis	1b	2b	1b	1b		2b	1b	1b		Warnell, K., et al. In press. Testing ecosystem accounting in the United States: A case study for the Southeast. Forthcoming in: Ecosystem Services

## **Supplementary Material #2. Biophysical accounts, mapping and modeling**

SEEA EEA's relevance is underlain by both its detailed spatial biophysical information and monetary value indicators. This section presents a brief overview of (i) how spatial variability is captured in the SEEA EEA; (ii) modeling and mapping approaches that have been applied to date, and (iii) next-generation data and modeling approaches that can support SEEA EEA.

**Spatial variability in SEEA EEA.** Spatial variability - the distance at which spatial variations in ecosystems become relevant to understanding their functioning and use - is captured in the SEEA EEA framework in two ways (6). First, through the extent account, a country is divided into specific ecosystem types. These ecosystem types are relatively homogenous units in terms of key ecological characteristics such as climate, vegetation, soils and hydrology (though ecosystem types can be further subdivided). Second, maps of ecosystem condition and ecosystem services supply show variation both between and within ecosystem types. Within ecosystem types, there is usually spatial variability in for example slope, groundwater depth, vegetation composition and ecosystem use. This is expressed in the condition and services supply accounts, which show how relevant indicators vary across the landscape. Spatial variability is also captured in the thematic accounts. Biodiversity and carbon stocks and flows, for example, are mapped as well as represented in accounting tables. Usually, accounts are produced based on annual accounting periods. However, indicators can be added to quantify variations in ecosystems within a year (e.g., mean or maximum NDVI over the duration of the growing season within a condition account).

Spatial variability can differ substantially between ecosystem types, reflecting geography and past and present land use. Boreal forests are more homogenous than western European agricultural landscapes, for instance. This can influence the resolution needed for ecosystem accounts produced following the SEEA EEA (16). In the Netherlands, for example, a resolution of a few meters is required to capture landscape elements such as hedgerows that are important for ecosystem functioning and biodiversity (17). However, ecosystem condition and services in Siberian boreal forests might be accurately represented using maps with a resolution of e.g., 100 meters or more. The largest challenge, clearly, is in mapping for large yet diverse countries. Doing so requires considerable data, sophisticated biophysical models that are customized for varying geographic contexts and substantial computing power.

Biophysical models are used in SEEA EEA to compile continuous, national-scale ecosystem extent maps, ecosystem condition maps that indicate the state of ecosystems and biophysical ecosystem service supply and use maps, which indicate ecosystem service use (6). Land use, biodiversity, carbon stocks and flows and water may be mapped in four thematic accounts. Mapping and spatial modeling for SEEA EEA builds upon an extensive literature (e.g., 16-21)). Mapping of ecosystem condition and services poses several challenges that are specific to SEEA EEA, which we briefly describe below.

*Mapping ecosystem condition.* Ecosystem condition accounts reflect the state and functioning of ecosystems, including key ecosystem components and processes (22). For example, condition indicators may provide information on nutrient and hydrological cycles, species composition and productivity and may include specific indicators reflecting ecosystem degradation. As best as possible given data availability, condition indicators should reflect key ecosystem properties that are relevant for the supply of ecosystem services. Examples include the presence and density of commercial timber species in a forest, or water quality indicators in ecosystems used for fish production and subject to pollution.

*Mapping ecosystem services.* In SEEA EEA, by definition, the quantity of ecosystem services supplied by an ecosystem equals the quantity of their use in the economy. Three types of services are distinguished (6): provisioning, regulating and cultural services. These reflect, respectively, the harvest and extraction of ecosystem goods (e.g., timber, fisheries), the regulation of ecological process beneficial to people (e.g., air filtration, flood regulation), and non-material uses of the ecosystems (e.g., recreation). The mapping of provisioning services is generally relatively straightforward, requiring the downscaling of statistical data, for instance on timber harvests (e.g., 23). The SEEA EEA records how the ecosystem contributes to economic activity, for instance by supplying standing stocks of timber. The harvested timber is recorded in the SNA, the supply of timber for harvesting is the ecosystem service. The monetary value of the service, in this case, reflects the value of the harvested timber minus the costs of harvesting. Regulating and most cultural services, however, cannot be directly related to an economic activity that is included in the SNA. These services need to be mapped and modeled, requiring substantial data on ecosystem properties, processes and uses. This is often computationally challenging. For example, modeling the regulation by ecosystems of water flows (in terms of volume, timing and quality) requires analyzing how ecosystems moderate water flows in the landscape. This requires spatially and temporally explicit data on rainfall, temperature, soils, slope, stream flow and water use. Obtaining data and model development is often challenging, particularly in developing countries (24).

**Modeling and mapping approaches applied in SEEA EEA.** A broad range of modeling and mapping techniques have been applied in the various SEEA EEA accounts published to date. Broadly, two types of models have been used – models that: (i) downscale statistical information as a function of ecosystem characteristics and (ii) simulate ecological processes based on ecosystem properties to analyze ecosystem services supply. Downscaling models have been used, for instance, to downscale timber production data from the Netherlands' national forest inventory to nationwide maps of the ecosystem service timber supply (18). The forest inventory provides data on timber harvest by administrative unit and tree species. These data were combined with detailed ecosystem extent maps to allocate timber supply by forest type across the country. Downscaling models were similarly used for SEEA EEA accounts in the EU, specifically for crop provision, timber provision, and carbon sequestration (25).

The second type of spatial models are often used to model regulating services and occasionally cultural services. These models assess the specific processes underlying ecosystem services, such as the deposition of particulates onto vegetation (filtering the air) or the action of plant roots in holding soil in place by ecosystems. Various models are used, ranging from simple (e.g., lookup tables) to more complex (e.g., geostatistical interpolation or process-based models). Examples include models of flood control, crop pollination, and recreation in the EU (25) and those for air and water filtration, crop pollination, carbon storage and avian biodiversity in the US (26). Model inputs are frequently generated from remote sensing products (27).

Several SEEA EEA accounts have used toolkits that address multiple ecosystem services using common interfaces and modeling frameworks (28). Examples include the Ecosystem Services Mapping Tool (ESTIMAP, 29), applied to EU accounts (25) and Integrated Valuation of Ecosystem Services Tradeoffs model (InVEST, 30) applied to SEEA EEA in Rwanda (31). An advantage of such toolkits is their ability to model multiple ecosystem services using a common framework (vs. e.g., multiple models with different interfaces or written in different programming languages), and comparability between accounts generated using the same modeling approach.

Importantly, all models are simplifications of reality – in this case complex linked ecological- socioeconomic systems – so tradeoffs exist when choosing between the many types of models that can be used to build accounts (32). Generally, modelers must consider different models' fit to the



decision context, the level of data and expertise available, and the transparency and trust that different models may have with users of the accounts.

An example of a map produced with SEEA EEA is provided in Figure A2.1 below (33). The maps show carbon emissions from peat oxidation in the Netherlands, expressed in tons of carbon (C) emitted per hectare per year (as recorded in the SEEA EEA Carbon account). Emissions are assessed based on soil type, drainage levels and density of drainage canals. National emissions from peat amount to around 2 Mton C per year. In the deepest drained areas, emissions are as high as 12.5 tons of C (or 45 tons of CO<sub>2</sub>) per hectare per year (equivalent to emissions from nine Dutch households). The carbon account shows high-priority areas for restoration. The ecosystem services supply account shows that the large majority of drained peatlands support dairy farming. That industry's per-hectare profits are roughly equal to CO<sub>2</sub> emissions costs (in deep drained areas), when these are valued at 48 euro per ton CO<sub>2</sub> (34). Costs of pumping and restoring infrastructure damage due to soil subsidence amount to an additional cost of 1000-1500 euro per hectare per year. Information from the Netherlands carbon accounts has been used to inform the policy and public debate on peatland uses (35); peatland restoration is part of the recent national climate action plan (36).

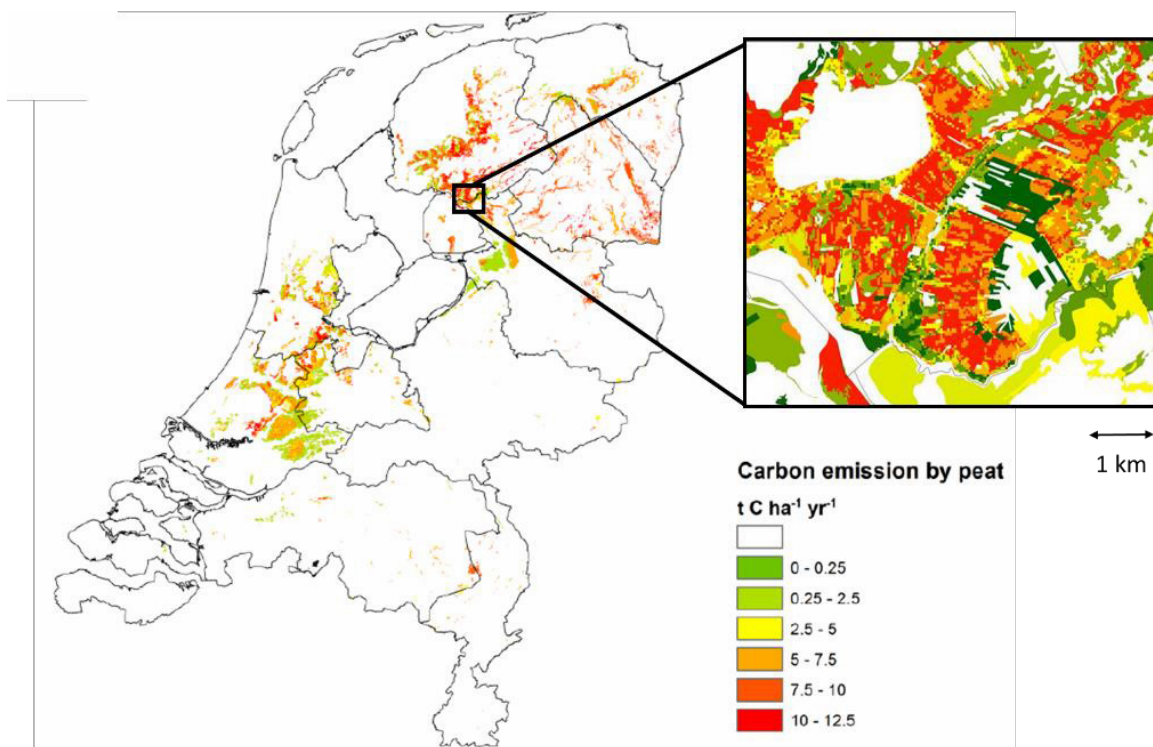


Figure A2.1. Carbon account map for the Netherlands, showing carbon emissions from peatland drainage (32).

**Next-generation modeling to support SEEA EEA.** Characteristic of the era of “big data,” a variety of new technical approaches are emerging that may make SEEA EEA modeling faster, more transparent, and higher quality, while improving the accessibility of SEEA EEA results and their application to decision making. We briefly describe five novel approaches below that could better inform future SEEA EEA applications. First, several global models of ecosystem services exist (37) and might be incorporated into SEEA EEA accounts. The benefits of their international consistency and comparability must be weighed against the increased trust and gains in accuracy that models typically gain when populated with local data (16). Second, the diversity and quality of remote sensing data has grown rapidly in recent years, offering many paths to improve the quality,

consistency, and accuracy of ecosystem accounts (27). Third, social media and citizen science offer ways to “crowdsource” information that may be amenable for use with SEEA EEA, particularly about cultural ecosystem services (e.g., 38,39). Fourth, machine learning algorithms offer new approaches to modeling that yield improved predictive power at the cost of the theoretical grounding characteristic of traditional process models (40). Emerging approaches like process-guided machine learning may offer the “best of both worlds,” combining the strengths of both process and machine learning models (41). Finally, the FAIR Principles, which suggest that scientific data should be Findable, Accessible, Interoperable, and Reusable by both human users and computers (42), are part of the larger open science movement. The Artificial Intelligence for Ecosystem Services (ARIES) project, which makes data and models accessible and interoperable on the web, is one such approach to making SEEA EEA data and models more FAIR (43). These approaches could make the application of biophysical models in support of SEEA EEA more feasible particularly in countries where data and technical capacity are limited.

### Supplementary material #3. Monetary valuation in the SNA and SEEA-EEA

This Annex briefly explains the relationships between the valuation principles guiding SNA and SEEA- EEA and between those principles and measures of welfare in economic terms.

**Valuation principles.** The general rules on valuation in the 2008 version of the SNA state that “the power of the SNA as an analytical tool stems largely from its ability to link numerous, very varied economic phenomena by expressing them in a single accounting unit. The SNA does not attempt to determine the utility of the flows and stocks that come within its scope. Rather, it measures the current *exchange value* [italics added] of the entries in the accounts in money terms, that is, the values at which goods, services, labour or assets are in fact exchanged or else could be exchanged for cash (currency or transferable deposits).” (3, paragraph 3.118). Note that the SNA concept of ‘exchange value’ refers to the price at which goods and services are or could be exchanged. In the main text of our Policy Brief we therefore use the term ‘exchange prices’ instead of ‘exchange values’.

The section “The SNA and measures of welfare” (3, paragraph 1.75) states that “GDP is often taken as a measure of welfare, but the SNA makes no claim that this is so and indeed there are several conventions in the SNA that argue against the welfare interpretation.” An example of such a convention is the exclusion of unpaid services from the production boundary (the limits of goods, services, and assets included and valued in accounts) used to define GDP. Note, however, that although excluded by convention these values can, in principle, be part of the national accounts.

**Welfare versus exchange values.** The focus on exchange values in SEEA EEA implies that the monetary values shown in the national accounts are not equivalent to a correct measure of welfare from an economic point of view<sup>1</sup>. In particular, the exchange values recorded in the transaction- based nature of the system<sup>2</sup> exclude consumer surplus while including producer surplus and production costs.

However, the literature has pointed out that by using index number theory<sup>3</sup>, it is possible to approximate a correct measure of welfare *change* from national accounts data using the prices and quantities pertaining to two periods of time (45). The literature has also shown that, as long as changes are marginal and a set of additional conditions are met; changes in societal welfare are approximated sufficiently well by changes in Net Domestic Product (NDP), which is calculated by subtracting depreciation from Gross Domestic Product (GDP). More precisely, in a dynamic model Weitzman (46) showed that marginal variations in NDP equal variations in welfare under a set of restrictive assumptions, which have been partially relaxed in subsequent studies (see (44) for a previous and similar result and (47) for a survey of this literature and a discussion about the assumptions needed).

The key point for the discussion at hand is that for this result to hold one needs to assume that all consumption services and capital stocks (assets) that are relevant to human wellbeing are correctly priced and included in the accounts. Thus, for this to hold all relevant natural capital and ecosystem services need to be included in the accounts to obtain an indicator that approximates welfare changes. By the same token, the (accounting) prices discussed in this literature are not focused

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<sup>1</sup> In a partial equilibrium context and ignoring wealth effects, economists measure changes in welfare estimating changes in the consumer and the producer surplus (the consumer surplus is the maximum amount that consumers would have been willing to pay in excess to what they actually paid for a good, and the producer surplus is the amount that producers obtained from selling a good, in addition to their costs). Hicksian variations are considered to be more precise measures of welfare, as they take into account general equilibrium and wealth effects. For details, see (44).

<sup>2</sup> The SNA uses a quadruple entry bookkeeping system that ensures consistency in recording transactions between multiple entities.

<sup>3</sup> An index number is the measure of change in a variable, or group of variables, over time. The literature has proposed different indexes to measure welfare changes (see (45)).

exclusively on those observed in current market transactions. Indeed, this is also true in principle for the national accounts since the SNA states that “when non-financial resources are provided without a quid pro quo, such resources should be valued at the market prices that would have been received if the resources had been sold in the market” (3, paragraph 3.130). Nonetheless, while measurement of these services and asset prices may be appropriate in principle, their inclusion is not standard SNA practice.

**Valuation in the SEEA EEA.** The objective of the SEEA-EEA (5) is to incorporate natural capital and ecosystem services into economic decision making by describing how the economy depends on the environment, as well as its impacts on it. The SEEA-EEA approaches its objective by extending the general principles of the SNA to environmental goods and services that are not included or not separately identified in the SNA. This allows compilation of integrated monetary accounts that capture the flow of ecosystem services and stocks of ecosystem assets, including measures of income and wealth adjusted for ecosystem degradation. To achieve this integration, it is necessary to maintain consistency with the SNA valuation principles. This consistency allows the inclusion of environmental goods and services in measures of economic activity and, using index number theory as discussed above, enables derivation of correct measures of welfare *change*.

The nature of this extension is consistent with the motivation, as discussed in (1), that future developments of the national accounts should be guided by the principles underlying national accounts rather than by current conventions (see (48) for a discussion about the integration of pollution in the national accounts). At the same time, as noted by (49, 1) and (2), while the national accounts should tackle the difficult task of measuring welfare and well-being, this work should be undertaken without forgetting the importance of current measures of economic activity, such as GDP, which also need ongoing refinement to adapt to new economic phenomenon (e.g., the digital economy).

To ensure a consistent extension to the SNA, ecosystem services and assets are thus valued in the SEEA EEA using prices based on the SNA exchange value concept, i.e., the prices at which goods, services or assets are, or could be, exchanged for cash (note that the SNA exchange price concept is, in principle, identical to the price as a marginal value concept used in economics). When traded in regular markets, exchange values are observable. However, following the SNA, “when market prices for transactions are not observable, valuation according to market-price-equivalents provides an approximation to market prices. In such cases, market prices of the same or similar items when such prices exist will provide a good basis for applying the principle of market prices. ... If there is no appropriate market in which a particular good or service is currently traded, the valuation of a transaction involving that good or service may be derived from the market prices of similar goods and services by making adjustments for quality and other differences.” (3, paragraph 3.123).

While this approach can be applied in a range of instances, for some ecosystem services, such as open-access, nature-based recreation or air filtration, there are often no markets where the same or similar items are currently traded in sufficient numbers and in similar circumstances. The Technical Recommendations document of the SEEA EEA (6: p. 97) therefore proposes to apply the concept of exchange values to include “those values that reflect the price at which ecosystem services and ecosystem assets would be exchanged between buyer and seller if a market existed.” In this framing, valuation approaches that are compatible with the principles of the SEEA EEA include, for instance, avoided damage costs methods and hedonic pricing. These methods do not generally provide a measure of welfare, i.e., including producer and consumer surplus (50). An innovative alternative solution, the Simulated Exchange Value (SEV) method, is to simulate the price and quantity that would have been observed if a similar good would have been traded in a market (51).

**Further research.** Although there is broad alignment on the principles and methodologies for valuing ecosystem services in the context of the SEEA EEA, further refinements are still being pursued. These include for instance (i) better defining the applicability of various valuation methods under different ecosystem management regimes; (ii) specification of the discount rate(s) and other assumptions to use in the valuation of ecosystem assets; and (iii) further exploring how to value cultural ecosystem services, where the appreciation of ecosystems often depends upon multiple types

of interactions between people and ecosystems (52, 53). These and other topics are being pursued in the SEEA EEA revision process currently underway.

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