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Review Paper

Lessons learned from development of natural capital accounts in the United States and European Union

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ABSTRACT

The United States and European Union (EU) face common challenges in managing natural capital and balancing conservation and resource use with consumption of other forms of capital. This paper synthesizes findings from 11 individual application papers from a special issue of *Ecosystem Services* on natural capital accounting (NCA) and their application to the public and private sectors in the EU and U.S. NCA is inherently a data-integration centered exercise, aiming to draw new insights by realigning environmental and economic data into a consistent framework. Drawing primarily on papers from the special issue and other key NCA literature, we identify lessons learned and gaps remaining for NCA's development and application to decision making. In doing so, we identify eight key similarities and three major differences in NCA development, status, and application between the U.S. and EU. NCA can be highly policy relevant: special issue papers address critical issues including agriculture, water, conservation/land-use planning, climate, and corporate decision making. In both the U.S. and EU, further application is needed to drive demand for the accounts' production. Based on these experiences, the U.S. and EU can be important leaders in cross-sector, international collaboration toward next-generation environmental economic accounts that advance global NCA practice.

1. Introduction

The United States and European Union (EU) share much in common. They form the world's largest developed economies built on highly diverse ecosystems that occupy large extents of land and water. Both are scientifically advanced, data-abundant environments that led the early development of national economic accounts from the 1930s to 1950s. Progress on natural capital accounting (NCA) is more recent; European countries began work on environmental accounts 30 years ago[1] with a focus on ecosystem accounts in the last 10 years, while the most recent efforts to develop NCA for the U.S. began in 2016. Natural capital refers to the stock of renewable and nonrenewable natural resources that are used by economic units (i.e., industries, households, and government), including flows of nonrenewable resources like energy and minerals as

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[1] The System of Environmental-Economic Accounting 1993 was the first effort to harmonize NCA approaches, although earlier experimental work on NCA took place in the 1970s and 1980s in countries including France, Norway (Smith, 2007), and the Netherlands.

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well as ecosystem services (United Nations, 2020). NCA provides physical and economic measurements of stocks of natural capital, including information on the extent and condition of ecosystems. NCA also provides information about the flows of ecosystem services that are used by various economic units. NCA—specifically the System of Environmental-Economic Accounting (SEEA) described below—allows environmental data to consistently link with the System of National Accounts, which provides guidance on how to produce conventional economic measures like Gross Domestic Product, expenditures, and asset values (United Nations et al., 2009). Limited treatment of natural capital within the System of National Accounts is one of its long-understood limitations (National Research Council, 1999).[2] NCA thus provides critical and systematized information needed to manage natural capital. The structure of NCA allows it to be used to assess tradeoffs between natural capital and other forms of wealth (e.g., built and human capital; Hein et al., 2020a; Boyd et al., 2018) through structured and consistent outputs. This gives it an advantage over the outputs of more generalized applications of ecosystem services modeling, mapping, valuation, and prioritization, although these methods themselves are often used in NCA. This paper highlights recent NCA advances in the U. S. and EU that are described in the *Ecosystem Services* special issue titled, “Accounting for Natural Capital: Lessons learned from applications in Europe and the United States.” Drawing lessons from these examples, we compare the various approaches and applications, identify continuing challenges, and suggest next steps for developing and using NCA most effectively.

Several approaches exist to systematically report the value of natural capital in physical and monetary terms, over time, and across industries and nations (Fig. 1). The SEEA is the only system explicitly designed to extend the System of National Accounts, integrating natural capital by applying consistent accounting rules and structure to environmental information. It is also the only NCA approach developed through extensive international collaboration and endorsed by the U.N. Statistical Commission, with the intent to provide comparability of results across nations and over time. The SEEA explicitly aims to assess and value ecosystems and their goods and services based on principles from the System of National Accounts. The SEEA Central Framework (SEEA CF, United Nations et al., 2014a) is an international statistical standard that documents links between the environment and the economy by quantifying stocks of environmental assets, environmental flows into and out of the economy, and economic activity related to the environment. Information about resources such as land (Wentland et al., 2020), water (Bagstad et al., 2020a), agriculture, fisheries, and forestry (Cerilli et al., 2020), minerals, and unintended production outputs such as pollution and waste (termed “residuals” in the SEEA) are combined into a coherent system that is fully compatible with the System of National Accounts. The SEEA Ecosystem Accounting framework (SEEA EA) quantifies ecosystems’ (1) extent and (2) condition plus the (3) supply and use of ecosystem services in both physical and (4) monetary terms, and finally (5) asset accounts that quantify the net present value of stocks of ecosystem assets (United Nations et al., 2014b, United Nations, 2017, United Nations, 2021a). Previously termed “Experimental Ecosystem Accounting,” SEEA EA underwent a revision process from 2019-2021 that culminated in its approval by the U.N. Statistical Commission in March 2021 (Edens et al., this issue, United Nations, 2021a).[3] Five papers in this special issue compile SEEA EA accounts (Capriolo et al., 2020, Hein et al., 2020b, Heris et al., 2021, Petersen et al., this issue, Vallecillo et al., 2020, Warnell et al., 2020a; Section 1.2). SEEA EA also includes thematic accounts covering specific topics that aid in the interpretation of ecosystem accounts, which include accounts for land, water, carbon, and biodiversity (United Nations, 2017); the recent SEEA EA revision (United Nations, 2021a) also describes thematic accounting approaches for oceans and urban areas (e.g., Heris et al., 2021).

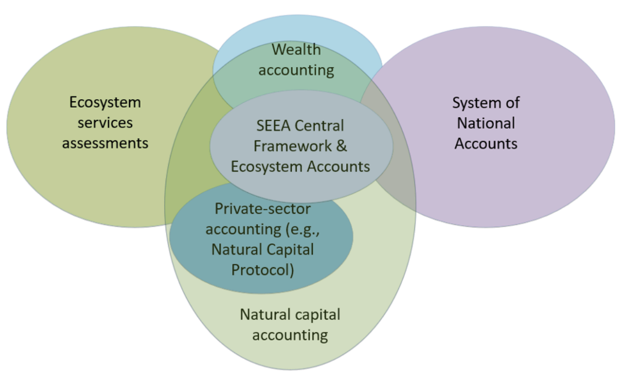

Fig. 1. The relationships between natural capital accounting frameworks, ecosystem services assessments, and the System of National Accounts.

Beyond the SEEA, wealth accounting assesses the value of natural capital *assets* (i.e., the present value of natural capital stocks), alongside built capital assets already included in the System of National Accounts, and human capital assets excluded from national accounts (Lange et al., 2018, UNEP, 2018). Private-sector approaches to measuring, valuing, and integrating natural capital into business decision making (e.g., Natural Capital Coalition, 2016) and NCA efforts are also diverse and growing, and may incorporate data and methods from both SEEA and ecosystem service assessments more generally (Houdet et al., 2020, Ingram et al., this issue). Unlike the SEEA, they need not be bound by the accounting rules of the System of National Accounts and may align with private accounting standards. Private-sector approaches typically have attempted to navigate the tradeoff between simplicity and ease of compilation on one hand and providing analytically meaningful data on the other, and have generally followed a company-by-company, bottom-up approach rather than the more top-down SEEA approach. Discussions are underway about how to develop data and tools that will assist private-sector efforts, providing the “glue” between public- and private-sector NCA (i.e., Capitals Coalition, 2020). For example, the Transparent Project has been funded by the EU to standardize natural capital accounting principles for the private sector (Natural Capital Coalition, 2020).

1.1. Why build natural capital accounts? the promise of better decision making

Building on the success of the System of National Accounts in informing policy and public dialogue around how nations manage their economies (and private-sector companies manage their assets), NCA

[2] Although the System of National Accounts includes “non-produced assets”—forests, land, water, fish, minerals, and sub-soil energy resources—on the National Balance Sheet, this is only a partial view of natural capital (Obst and Vardon, 2014) and many countries do not compile a complete National Balance Sheet. The *production boundary* defines which components related to economic production are included and excluded in an accounting system. In the System of National Accounts, the above components of natural capital are included in the production boundary while other key elements of natural capital, such as regulating and cultural services, are not. Implementation of the existing system boundaries can be challenging enough for many national statistical offices.

[3] The U.N. Statistical Commission approved the chapters of the SEEA EA covering biophysical accounting (ecosystem extent, condition, and physical supply and use) as a statistical standard. It simultaneously recognized the less mature state of monetary supply and use and asset accounting, and recommended that further research on these topics continue (Brown et al., 2021, Edens et al., this issue).

uses accounting concepts and definitions to more systematically track the quantities and values of natural capital stocks and ecosystem service flows (Gleeson-White, 2015, Boyd et al., 2018). We revisit the use of NCA in policy and decision making in U.S. and EU contexts in Section 2; however, some general themes on the role of NCA in decision making are important to set the stage. Overall, NCA enables broad, cross-sector policy discourses about natural capital and its role in the economy by providing consistent and systematically generated information (Vardon et al., 2017). NCA can be used to monitor stocks and flows of market and especially nonmarket goods and services provided by natural resources, which are regularly omitted from both national and corporate balance sheets (Boyd et al., 2018). This information has supported evaluation of natural resource management performance and outcomes, while being used to more rigorously define and assess the sustainability of the economy and business (Obst, 2015).

NCA provides important advantages for decision makers. It provides a consistent framework for the reporting and analysis of past trends and present conditions. For example, water accounts can provide information about the timing, location, and severity of water scarcity, and can be used to evaluate likely risks to water users across economic sectors and the consequences of alternative management approaches (Bagstad et al., 2020a). Governments can use NCA to weigh the tradeoffs between investments in the protection or improvement of upstream ecosystems versus investments in water treatment facilities (La Notte and Marques, 2017). Moreover, a system-scale perspective of water and other ecosystem services can reveal both inefficiencies and opportunities within the linked natural-human system. From a macroeconomic perspective, NCA assembles ecological and economic information in a structured and harmonized way, with the aim of consistency and compatibility between the System of National Accounts and the SEEA. This allows researchers to bridge conventional economic tools such as multiregional input-output tables and general equilibrium models, enabling the evaluation of scenarios representing policy alternatives against historical baselines (Banerjee et al., 2020, La Notte et al., 2020, Roxburgh et al., 2020). SEEA data can also be directly integrated into models in order to jointly predict economic and environmental outcomes of policy decisions. For example, Banerjee et al. (2020) integrated a macroeconomic model for Rwanda with SEEA CF and SEEA EA data and models to evaluate the impacts of alternative development strategies on Rwanda's economy, land and water use, and ecosystem services, in a manner comparable with Rwanda's baseline SEEA EA accounts (Bagstad et al., 2020b). La Notte et al. (2020) linked ecosystem accounts with a macroeconomic model to assess the impact of pollinator declines on agricultural production, imports, and exports in the EU.

A growing set of policy decisions exists that use NCA to inform decision making. For instance, Ruijs et al. (2018) note the use of NCA information in 17 nations across all five stages of the policy cycle—issue identification, policy response, policy implementation, policy monitoring, and policy review. Despite some success stories to date, more work remains to fully understand how NCA can inform policy and management decisions across the full range of different contexts and stakeholders (Green Growth Knowledge Partnership, 2020, see also Section 2). Some of this can be accomplished by identifying and understanding specific information needs for managing natural capital, for example, how NCA can support achievement of specific policy targets in the EU's Environment Action Programme (EEA, 2019). Critically, Vardon et al. (2016) note that for NCA to fully succeed and move toward institutionalization, a "policy pull," i.e., a strong and consistent demand for NCA information by users, is needed, rather than just an "accounting push" by NCA practitioners who build accounts and suggest their usefulness for decision making. Others have noted a gap between the more widespread production of NCA data and its more limited use in decision making in both the public (Virto et al., 2018) and private sectors (Ingram et al., this issue) and discuss ways to close this gap.

1.2. The NCA landscape in the U.S. and EU

The EU and U.S. both have large geographies, economies, and populations, though political differences shape how each has developed and used NCA information. Critically, the U.S. government is a Federal system while the EU is a supranational one. The U.S. government compiles official statistical and environmental data for the nation that are used by multiple levels of government—Federal, State, and local—as well as by nongovernment users (Fig. 2). By contrast, EU statistical data are compiled by Eurostat, the EU's statistical office, integrating mainly national (or regional) data as reported by member states. EU-level statistical data can be integrated in EU accounting systems using consistent data and methods (Vallecillo et al., 2020). However, ecosystem accounts are also developed by national governments using their best-available science, national data, and preferred methods (e.g., Capriolo et al., 2020, Hein et al., 2020b, MAIA, 2020). Ecosystem accounts require skills beyond the traditional expertise of most statistical agencies, such as the use of spatial data and environmental modeling, which require collaborations with ecologists, physical scientists, and geographers as well as accountants and economists. SEEA accounts (particularly SEEA EA) thus generally require collaboration between statistical and science agencies, along with increasing interest and support from space agencies that provide needed remote sensing-derived data products. These agencies can be more or less centralized. The U.S. is an example of a decentralized statistical system (Fig. 2, bottom left), with 13 agencies having production of statistical information as a core responsibility; the Bureau of Economic Analysis compiles the National Income and Product Accounts, the U.S. implementation of the System of National Accounts. Production of the System of National Accounts in the European Statistical System is the responsibility of each member state's national statistical office. Eurostat receives and publishes these data and also produces EU and euro area aggregates. Fig. 2 shows how in some cases

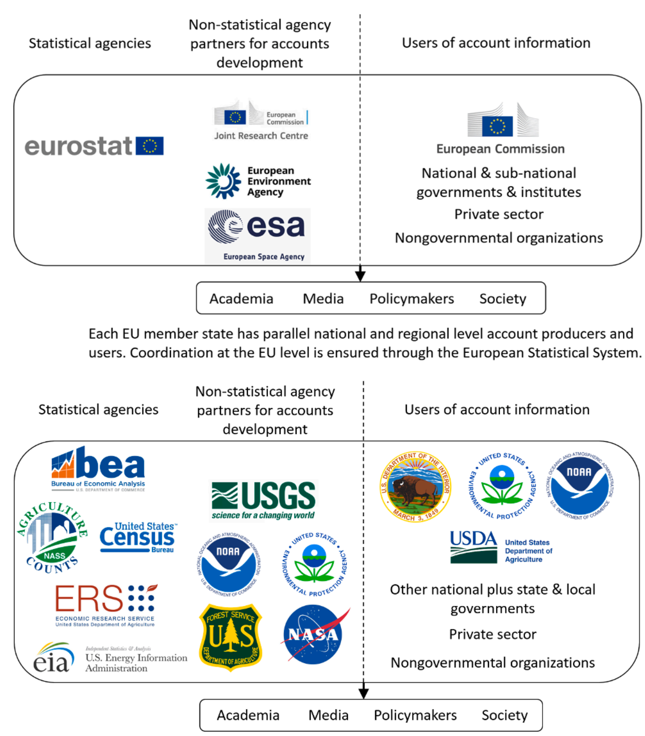

Fig. 2. Natural capital accounting (NCA) producers (left) and current and potential users (right) in the European Union (top) and the United States (bottom). Dialogue between producers and users of NCA (left and right sides) is critical to aligning accounts with societal needs. Academia, the media, policymakers, and society shape the dialogue around economic accounts and could do the same for NCA.

government agencies can both assist in the production of NCA information and be information users—particularly when an agency has a joint scientific and regulatory/resource management mandate, as is often seen in the U.S. Additionally, policymakers, the media, and society play key roles in public policy discussions informed by System of National Accounts information (Hoekstra, 2019), and could play similarly greater roles in the future NCA landscape. Academics play similar roles and also, critically, develop experimental data and methods that are eventually incorporated into NCA production processes.

The two regions also differ in their histories of producing and using accounts information. In the EU, the compilation of SEEA CF accounts started with independent country compilations of accounts in the early 1990s. These efforts were followed by the formation of task forces, supervised by Eurostat, the EU's statistical office, that built specific accounting modules: a national accounting matrix including environmental accounts, environmental protection expenditure accounts, forest accounts, and material flow accounts. This work paved the way for a Regulation on European environmental economic accounts: Regulation (EU) No 691/2011 (European Commission, 2011a). This regulation mandates that EU member states compile six modules included in the SEEA CF: air emissions accounts, economy-wide material flow accounts, physical energy flow accounts, environmental taxes, environmental goods and services sector accounts, and environmental protection expenditure accounts. Ongoing work addresses additional environmental accounts, with no EU legal requirement, such as forest accounts, and accounts for environmental subsidies and similar transfers. These accounts are now part of the statistical information available in the Eurostat database (Eurostat, 2020). In early 2020, Eurostat began work on a proposal to amend Regulation 691/2011 to propose new modules to be covered, specifically for ecosystem accounts. The proposal for the new ecosystem accounts modules is still under development and will require a long and complex approval path (Vysna and de la Fuente, 2020).

At the national scale, pioneering work on SEEA EA has been undertaken during the past decade in the Netherlands (Hein et al., 2020b, Horlings et al., 2020) and the United Kingdom (Natural Capital Committee, 2013). Since 2017, Eurostat has co-financed SEEA EA projects in EU Member States including Bulgaria, Denmark, Estonia, Finland, Hungary, Italy, the Netherlands, Sweden, and the United Kingdom (an application for Italy is reported in this issue by Capriolo et al., 2020). Most of the project proposals addressed extent and condition accounts and provisioning and regulating services, with few applications for cultural services. At continental scale, the Integrated system for Natural Capital and ecosystem services Accounting (INCA) was set up in 2015 by the European Commission and the European Environment Agency. INCA supports the expansion of SEEA EA in the EU, building on the EU initiative on Mapping and Assessment of Ecosystems and Services (MAES), which aims to map, assess, and value ecosystems and their services in the EU. INCA developed a set of EU-level ecosystem extent, condition, and services accounts (Vallecillo et al., 2020, Vysna et al., 2021). The European Commission has also funded research projects under its Horizon 2020 program, such as MAIA (Mapping and Assessment for Integrated ecosystem Accounting) mentioned in Hein et al. (2020b) and We Value Nature (We Value Nature, 2020), which supports the integration of NCA information into private-sector accounting.

NCA in the U.S. is much newer. Preliminary work on mineral accounts was conducted in the 1990s (Carson, 1995), and recommendations were made to continue and expand this work (National Research Council, 1999). Following the release of the SEEA CF and SEEA EA guidelines in the early 2010s, experimental work on SEEA accounts began in late 2016 as a collaboration between a number of U.S. government agencies (Fig. 2) (Boyd et al., 2018). Additionally, the Bureau of Economic Analysis has recently collaborated with the National Oceanic and Atmospheric Administration on ocean accounts (Nicolls et al., 2020) and the Departments of Agriculture and the Interior on outdoor recreation accounts (Highfill and Smith-Nelson, 2018). While not SEEA accounts, this work entailed broader interagency cooperation with natural resource management agencies and shows the importance of natural resources in underpinning market activity. Academic NCA work in the U.S. has estimated the value of groundwater in Kansas from a wealth accounting perspective (Fenichel et al., 2016) and produced SEEA EA accounts for Long Island's South Shore Bays (Dvarskas, 2019). The U.S. pilot accounts included in this special issue demonstrate the feasibility of compiling natural capital accounts while identifying remaining data gaps that will enable the construction of more rigorous and regular accounts in the future. However, given the much more recent state of U.S. NCA, they are in most cases less complete than second- and third-generation European accounts and have a more limited history of use in decision making.

In this paper, we synthesize results from applied NCA papers in the EU-U.S. special issue on NCA, highlighting key commonalities and differences, their current and potential use in decision making, and next steps for NCA in the U.S., EU, and elsewhere. Our assessment includes examples using SEEA CF, SEEA EA, and private-sector accounting frameworks (Table 1). It includes supranational work for the entire EU, as well as two accounts for EU nations and a private-sector NCA application in France. U.S. applications took place at national and subnational scales. Section 2 discusses application of the accounts to policy and decision making in the U.S. and EU. Section 3 addresses technical aspects of NCA applications from the special issue, identifying three key differences (Section 3.1) and seven key similarities (Section 3.2) between accounts compiled for the U.S. and EU, and implications for future NCA work there and globally. In Section 4, we conclude by highlighting challenges and opportunities surrounding further application of NCA worldwide based on experience in the EU and U.S.

2. Applying NCA for decision making in the U.S. & EU

The raison d'être of NCA is to inform better decision making, both in public and private applications (Vardon et al., 2016, Boyd et al., 2018, Ruijs et al., 2018, Green Growth Knowledge Partnership, 2020, Ingram et al., this issue). Reflecting this importance, the World Bank has hosted annual workshops on this topic since 2016, with publications describing diverse applications, "use cases," and lessons learned (Vardon et al., 2017, Vardon and Bass, 2019; Vardon and Bass, 2020); efforts to develop more use cases of NCA are underway globally. However, a gap often remains between the aspirations for NCA in policy use and actual uptake (Vardon et al., 2016, Virto et al., 2018, Green Growth Knowledge Partnership, 2020, Ingram et al., this issue). Despite this gap, NCA may play an important role through conceptual use—with information applied to frame ideas and shape policy thinking rather than, for instance, to "decide between alternatives A and B" (Meagher and Lyall, 2013, Yanovitsky and Weber, 2020). Such cases may be difficult to document relative to instances of direct use to make a concrete decision, particularly in nations where NCA is new and at an early stage of its impact pathway, like the U.S. Nearly all of the papers in this special issue discuss the policy use of accounts explicitly, some in great detail (e.g., Bagstad et al., 2020a, Hein et al., 2020b, Ingram et al., this issue), with the aim of closing this gap (Box 1).

NCA's use in European policy has been described in substantial depth elsewhere (EEA, 2019), including in the background technical reports (Vallecillo et al., 2018, 2019) that underlie Vallecillo et al. (2020). A recent audit on the application and policy uses of the SEEA CF accounts in the EU and its member states carried out by the European Court of Auditors (2019) concluded that the various environmental accounting modules were not used to their full potential for monitoring key environmental policies. EU policy uptake of ecosystem accounts has started slowly but is gradually increasing. The EU-level ecosystem accounts developed under the INCA project (Vallecillo et al., 2019) increasingly find their way into concrete policy initiatives of the European Commission. These include the EU policy on pollinators, the framework for sustainable investment, and the proposal for a nature restoration law.

Table 1
Summary of SEEA application papers in the special issue, excluding the introduction to the special issue (La Notte et al., this issue) and a paper presenting the SEEA EA framework and its history (Edens et al., this issue). SEEA CF: System of Environmental-Economic Accounting, Central Framework. SEEA EA: System of Environmental-Economic Accounting, Ecosystem Accounting.

Paper	Accounting framework	Geographic scope	Accounting focus	Assessment years
Capriolo et al. (2020)	SEEA EA	Italy	Ecosystem services (Flood mitigation, pollination, recreation, water supply)	2018
Cerilli et al. (2020)	SEEA Agriculture, Forestry and Fisheries (SEEA CF & SEEA EA)	European Union	Ecosystem services (Biomass provision, 8 crops)	2012
Hein et al. (2020b)	SEEA EA	Netherlands	Ecosystem extent, condition, services (Air filtration, amenity value, biomass provision (crops, fodder, timber), flood mitigation, global climate regulation, pest control, pollination, recreation, soil erosion control, water supply) Thematic accounts (Biodiversity)	2006, 2013
Houdet et al. (2020)	Private sector	Two sites in southern France	Thematic accounts (Biodiversity offsets)	Before & after development projects
Petersen et al. (this issue)	SEEA EA	European Union	Ecosystem extent	2000, 2006, 2012, 2018
Vallecillo et al. (2020b)	SEEA EA	European Union	Ecosystem services (Biomass provision (crops, timber), Global climate regulation, flood mitigation, pollination, recreation)	2000, 2006, 2012
Bagstad et al. (2020a)	SEEA CF (Water)	United States	Thematic accounts (Water physical supply & use, productivity, quality, emissions, water quality-use linkages)	2000–2015
Heris et al. (2021)	SEEA EA	768 cities in the continental U.S.	Ecosystem extent, condition, services (Local microclimate regulation, water flow regulation)	2011, 2016
Ingram et al. (this issue)	Private sector	United States	General use of NCA by businesses	N/A
Warnell et al. (2020a)	SEEA EA	10-state region in Southeastern U.S.	Ecosystem extent, condition, services (Air filtration, global climate regulation, pollination, recreation, water purification), Thematic accounts (biodiversity)	2001, 2006, 2011
Wentland et al. (2020)	SEEA CF (Land)	Continental U.S.	Thematic accounts (Land cover, use, value)	2001–2016

These policy initiatives, which are all included in the European Green Deal, are based on the principles of ecosystem accounting or use the results of ecosystem accounting for reporting or impact assessment. Although ecosystem accounts have been used in the initiatives mentioned above, overall uptake of ecosystem accounting results in key policy areas such as trade, agriculture, economy, and finance remains limited. The previously experimental nature of ecosystem accounting, the currently laborious production of these accounts, and the uncertainty surrounding the physical and monetary estimates of ecosystem services (and even more so ecosystem assets) have to date remained obstacles for the mainstreaming of ecosystem accounts into other policy areas in the EU (Vysna et al., 2021).

Co-development of accounts with decision makers can be very useful in maximizing information relevance and making decision makers aware of NCA production efforts. As a good example of this, Hein et al. (2020b) incorporated an advisory group in the Netherlands that aimed to maximize the decision relevance of Dutch SEEA EA accounts. The integration of NCA with traditional economic tools has also been explored in the EU with the LInking accounts for ecosystem Services and Benefits to the Economy THrough bridging (LISBETH) project. This project developed initial applications (1) targeting consumption-based accounts to quantify imports and exports of water purification embedded in agricultural imports and exports (using multiregional input–output tables) and (2) linking with general equilibrium models through an example of how invasive species impact crop pollination, as an economic shock propagated through a computable general equilibrium model (La Notte et al., 2020). In LISBETH, better correspondence with the policy cycle (Vardon et al., 2016, Ruijs et al., 2018) is proposed to more effectively facilitate NCA use.

Given the relatively newer state of NCA in the U.S.—with the first accounts released in 2020—uptake in U.S. decision making has to date been limited. Notable outreach efforts to raise awareness of NCA and improve its use in decision making thus far include (1) discussions with stakeholders on how to apply water accounting to water resource management in Hawai'i, (2) work to integrate urban ecosystem accounts into decision making with cities around urban forestry and climate resilience issues (Box 1), and (3) ongoing collaboration with the Department of the Interior's Office of Policy Analysis to use NCA in decision making for the Department, which manages over 450 million acres of public land in the U.S. Parallel to the original U.S. NCA effort, environmentally extended input–output analyses have been developed by the U.S. EPA (Yang et al., 2017). These are primarily used by the private sector to assist in benchmarking and development of impact reduction strategies for resource use and emissions. Opportunities exist to better integrate NCA and environmentally extended input–output modeling to deliver improved environmental-economic data for public and private sector uses. Finally, the recent development of natural capital-adjacent satellite accounts in the U.S. is noteworthy. Satellite accounts are built on the foundation of the System of National Accounts but focus on a particular aspect of economic activity, expanding analytical capacity by using alternative industry definitions and focusing on relevant subsets of economic activity (United Nations et al., 2014a). The U.S. Bureau of Economic Analysis recently created satellite accounts that focus on two sectors of the U.S. economy, outdoor recreation (Highfill and Smith-Nelson, 2018) and the ocean economy (Nicolls et al., 2020), which are heavily dependent on underlying natural capital. Statistical agencies in EU countries including Ireland (Tsakiridis et al., 2019) and Portugal Simões et al. (2018) have also created ocean economy satellite accounts using similar methods. Although these accounts are defined based on natural resource dependency, they are not true examples of ecosystem accounting, but reframings of information supplied in the System of National Accounts. They do not directly measure the health of the underlying natural capital or the flow of ecosystem services into these industries. However, a decline in output detected by these accounts could signal underlying problems with the flow of ecosystem services. The creation of these accounts in the U.S. signals a clear recognition that certain industries are highly dependent on natural capital and that the investment to track their health is worthwhile. Satellite accounts could be another effective tool for NCA, and can identify economic activity that is clearly dependent on a flow of ecosystem services, which can populate the use side of SEEA supply and use tables. Identifying the ecosystem services that make up the supply side of this table would provide important additional information to industry and resource managers.

Box 1
Three examples of the application of natural capital accounts to policy.

Example 1: Water accounting on an island allows improved management of water availability and water quality risks. Initial U.S. water accounts (Bagstad et al., 2020a) are now being expanded to support decision making in Hawai'i. Water resource source protection, water supply, and wastewater management in Hawai'i are managed by three separate government agencies, which themselves are outside the agency responsible for economic and tourism development. Conflicts regularly ignite related to water use, land management, and wastewater reuse and disposal, and are expected to worsen in the face of climate change and population growth. Hawai'i has sustainable green growth goals related to water, but the water account is the first system-scale dataset available. Local impact investment firms, nongovernmental organizations (NGOs), water users, and government agencies are interested in using the accounts to better make allocation decisions, reward best management practices, understand water-related risks, design high-impact investments, and eventually propose legislation and administrative actions. In this case, timely production of a water account and outreach to decision makers has helped generate demand for more and better NCA information.

Example 2: Urban SEEA EA for city planning. Despite the relative scarcity of green space in cities, denser urban populations and economic activities disproportionately benefit from urban ecosystems. Implementation of urban ecosystem accounts is currently in a more exploratory phase than other SEEA EA accounts (La Notte, 2018). However, there is growing interest in urban ecosystem accounting (e.g., Anderson, 2018; Heris et al., 2021). While local governments may not be familiar with SEEA, they use similar frameworks, such as urban tree inventories and climate action plans, to track ecosystem services like heat mitigation and flood mitigation, plus associated vulnerability and equity issues. SEEA EA may thus provide a structured, time-consistent approach that resonates well with cities. The U.S. ecosystem accounting project has been working with several departments of New York City's government to customize Heris et al.'s (2021) ecosystem accounting models to inform the city's tree planting programs and Cool Neighborhoods Initiative.

Example 3: Reducing externalities through corporate natural capital accounting. Houdet et al. (2020) propose a net impact accounting framework that could help businesses understand and mitigate their impacts on the condition and extent of natural capital. The proposed accounting framework provides a relatively simple extension of current business asset and income/loss double-entry accounting through standardized reporting of "natural capital balance sheets" and "natural capital gain/loss statements." Such reporting would provide important transparency to investors, policymakers, and regulators on the health of the business, its sustainability, and its societal costs or benefits. The proposed framework could improve the quality and speed of business responses to changes in internal or external business conditions, including changes in natural capital or in regulatory frameworks. Houdet et al. give several examples of how net-impact NCA could be implemented and the benefits that could be achieved by scaling up such approaches.

By quantifying ecosystem extent, condition, and services in a spatial manner, tracking their changes over time, and making data available to the public, NCA has the potential to address a very wide range of economic and natural capital planning and policy issues. NCA papers in the special issue both directly reference application toward a variety of policy issues or implicitly do so through the ecosystem services they include in the accounts (Table 2). The papers in this special issue also enable comparisons of synergies and tradeoffs among ecosystem services, show how critical ecosystem services directly support economic activities, frame the role of ecosystem services through the supply chain, and improve the comprehensiveness of sustainability assessments. A U.S. example shows how combined presentation of land, water, ecosystem, and economic accounts can provide a more complete view of linked environmental-economic trends (Warnell et al., 2020a). A European assessment of "unmet ecosystem service demand" (Vallecillo et al., 2020) provides important information to policymakers on where ecosystem restoration can help to meet human needs, while supporting natural resource planning to meet conservation and development goals (Capriolo et al., 2020, Hein et al., 2020b).

As illustrated by the papers, NCA is designed to support decision making across a range of scales—from international to site level. Internationally, the consistency enforced by SEEA makes it a potentially effective way for countries to report on global conventions and agreements such as the U.N. Framework Convention on Climate Change, Convention to Combat Desertification, Convention on Biological Diversity, and Sustainable Development Goals (SDGs). Several special issue papers note the ability of SEEA accounts to inform reporting on the SDGs (Bagstad et al., 2020a, Cerilli et al., 2020, Hein et al., 2020b), and others have noted similar potential to inform reporting to the Convention on Biological Diversity (Nature, 2020). Despite this potential, integration of SEEA data with existing supranational or global reporting systems may require further work to adapt it to these purposes (Hein et al., 2020a). Papers from the special issue also provide information that could inform decisions at supranational and national scales in Europe (Capriolo et al., 2020, Cerilli et al., 2020, Hein et al., 2020b, Petersen et al., this issue, Vallecillo et al., 2020) and national or state levels in the U.S. (Bagstad et al., 2020a, Warnell et al., 2020a, Wentland et al., 2020). NCA can also be useful for decision makers in cities or, potentially, even for site-level land management. However, the use of national NCA data at fine scales will typically require its validation to ensure the accuracy and trustworthiness of the data (Hein et al., 2020b, Heris et al., 2021, Houdet et al., 2020).

3. Differences, commonalities, and lessons learned in U.S. And EU NCA applications

Beyond the common challenge of making NCA information more regularly used in decision making at all levels (Section 2), we identify three key differences (Section 3.1) and seven additional commonalities (Section 3.2) between NCA applications in the U.S. and EU here, and also discuss their implications for NCA in other parts of the world (Table 3).

3.1. Key differences between U.S. and EU NCA applications

3.1.1. Different history and institutionalization affect NCA content and use

An obvious distinction in the special issue papers is the more advanced and complete state of European SEEA accounts. U.S. accounts are first-generation, proof-of-concept approaches, and as such begin with land and water accounts. These accounts are often the first completed, because they offer important information to aid in interpreting trends in SEEA EA accounts (for this reason land and water accounts are classified as both SEEA CF accounts and SEEA EA thematic accounts). European accounts are often second- and third-generation accounts, and are mainly driven by the objectives set in the EU Biodiversity Strategy to 2020 and repeated in the 7th Environment Action Programme to develop natural capital accounts in the EU, with a focus on ecosystems and their services (European Commission, 2011b). Both U.S. and EU land and ecosystem extent accounts generally rely on land

Table 2
Economic and resource management issues explicitly or implicitly addressed by natural capital accounting application papers in the special issue. SEEA CF: System of Environmental-Economic Accounting, Central Framework; SEEA EA: System of Environmental-Economic Accounting, Ecosystem Accounting.

Issue	Special issue papers											% of papers addressing issue
	Capriolo et al. (2020) (SEEA EA, Italy)	Cerilli et al. (2020) (SEEA CF-Agriculture, Fisheries, & Forestry, European Union)	Hein et al. (2020b) (SEEA EA, Netherlands)	Houdet et al. (2020) (private-sector NCA, France)	Petersen et al. (this issue) (SEEA EA-Ecosystem extent, European Union)	Vallecillo et al. (2020) (SEEA EA, European Union)	Bagstad et al. (2020a) (SEEA CF-Water, U.S.)	Heris et al. (2021) (SEEA EA, U.S. cities)	Ingram et al. (this issue) (private-sector NCA)	Warnell et al. (2020a) (SEEA EA, Southeast U.S.)	Wentland et al. (2020) (SEEA CF land, U.S.)	
Agricultural planning & policy	X	X	X		X	X	X			X	X	73%
Water & watershed management	X		X		X	X	X	X		X	X	73%
City/regional & general land-use planning	X		X		X	X		X		X	X	64%
Climate adaptation & mitigation	X		X		X	X	X	X		X		64%
Conservation planning / ecosystem restoration			X		X	X		X		X	X	55%
Corporate decision-making & disclosure		X	X	X					X			36%

Table 3
Key differences and commonalities from natural capital accounting (NCA) applications developed for the U.S. and European Union (EU). ARIES for SEEA: Artificial Intelligence for Environment & Sustainability for System of Environmental-Economic Accounting; MAIA: Mapping and Assessment for Integrated ecosystem Accounting.

	Issue	Relevance to U.S. & EU NCA	Relevance to NCA applications in the rest of world
U.S.-EU differences (Section 3.1)	1. Varying history & level of institutionalization	Longer history & institutional buy-in of NCA in EU vs. U.S.—longer history of production, more accounts extended to valuation in the EU.	Countries with a longer history of producing accounts may have greater familiarity & comfort with assumptions needed to estimate certain ecosystem service values.
	2. Approaches to ES classification	Choice of CICES vs. NESCS or not to use a full classification has implications for how ecosystem condition & supply-use accounts may be represented.	The reference list of ecosystem services used in the SEEA EA supply and use accounts (SUA) is not a classification (United Nations, 2021a, paragraph 6.46, Finisdore et al., 2020), but an attempted comprehensive list of flows of final services that includes select intermediate services (use column types differ). Careful attempts to follow the SEEA EA guidelines for SUA construction should remain largely compatible with CICES and NESCS Plus (Newcomer-Johnson et al., 2020) classifications and "…to allow those using existing classification systems to link to the reference list, correspondences to CICES and NESCS are being developed and will be available as an online supplement to SEEA EA" ((United Nations, 2021a), paragraph 6.46).
	3. Variation in modeling methods	A variety of modeling methods can be used as long as they follow NCA conventions (i.e., SEEA); trust, replicability, interoperability, scale, data availability, & country expertise matter & may guide choice of methods.	Recent U.N. guidance on biophysical modeling can be useful for countries to navigate tradeoffs inherent in different approaches (United Nations, 2021c).
U.S.-EU commonalities (Section 3.2)	1. Underuse in decision making; greater use needed to fill NCA's promise (Section 2)	Better knowledge coproduction & stakeholder outreach needed (e.g., Hein et al., 2020b).	Well-known problem that applies to rest of world (Vardon et al., 2016, Virto et al., 2018, Green Growth Knowledge Partnership, 2020).
	2. Successful use of diverse data sources	Private sector, crowdsourced, Earth Observation data used in various accounts; novel uses may be replicable elsewhere to improve accounts.	Availability of such data is variable in developing nations; novel uses may be replicable elsewhere to improve accounts.
	3. Key data gaps remain	Important NCA data gaps remain even in data-abundant regions (e.g., for beneficiaries & land use).	These & other data gaps remain outside the U.S. & EU as well, U.S. & EU research can guide future efforts.
	4. Scales of analysis matter; challenges remain to data development at certain scales (e.g., watersheds, supply chains)	Local changes may be obscured at national to regional scale. Reporting of statistical data by administrative unit can make watershed-scale accounting challenging & require modeling; internationally consistent data & approaches are needed for private-sector NCA across supply chains.	Similar principles and modeling challenges apply beyond U.S. & EU.
	5. Simple models may not be good enough for U.S./EU	Data-abundant regions need to translate best-available science into NCA models; while attractive as initial steps, simpler or proxy-based methods are less likely to be deemed adequate by U.S. and EU science & policy communities.	Issue is also likely to be relevant in data-abundant regions outside the U.S. & EU.
	6. Centralized & replicable data/model management strategies needed	Code repositories, interoperability-focused approaches (e.g., ARIES for SEEA, United Nations, 2021b), & international collaborations like MAIA (2020) can make accounts compilation more reliable & replicable.	These approaches are a good way to diffuse scientific knowledge from data-abundant nations to the Global South, especially when easy to implement (e.g., ARIES for SEEA).
	7. Best practices in ecosystem services modeling (e.g., uncertainty, customization, actual ecosystem service flows, separating ecosystem and economic contributions using official statistical data)	Good examples of best practices exist in special issue papers but are not uniformly applied.	Special issue papers & other NCA/ecosystem services literature describe how other nations can best apply these principles to develop robust accounts.
	8. Spatiotemporal resolution & latency	High-resolution data generally available in U.S. & EU, provide a good basis for most modeling (but may be limiting for urban applications, Heris et al., 2021); longer time series & reduced latency would strongly benefit NCA.	Adequate spatial resolution, time series length, & latency are more likely to be limiting factors in data-scarce parts of the world.

cover to distinguish ecosystem types, but EU ecosystem extent accounts discuss paths forward to reporting on ecosystem extent rather than just land cover (Petersen et al., this issue). Similarly, water accounts reported in this special issue are the first ever for the U.S. (Bagstad et al., 2020a), while the EU already has systems for integrated and repeated reporting of water accounts (European Environment Agency, 2013). Cerilli et al. (2020) also provide a novel example of how the new SEEA Agriculture, Forestry and Fisheries standard that links System of National Accounts, SEEA CF, and SEEA EA can produce a "sustainability scorecard" for EU crop provision that also includes imports and exports by nation.

When faced with data limitations, U.S. papers may be more conservative in producing supply and use accounts than their European counterparts. As a key example, SEEA EA accounts for the EU, Italy, and the Netherlands produced physical and monetary supply and use tables for crop pollination (Capriolo et al., 2020, Hein et al., 2020b, Vallecillo et al., 2020). Their U.S. counterparts, however, produced a series of biophysical pollination metrics that were left as ecosystem condition indicators (Warnell et al., 2020a). The EU has a relatively long history of systematic national- and supranational-scale mapping and assessment of ecosystem services in the EU through the MAES initiative (Maes et al., 2016, Burkhard et al., 2018). This provides a strong foundation of spatially explicit data for ecosystem service accounts. By contrast, ecosystem service assessments in the U.S. have more frequently tended to be conducted at local to sub-national scales. The earlier-stage U.S. accounts may thus require a more meticulous and conservative approach to build confidence and buy-in to the SEEA approach among U. S. scientific and policy communities (see Fig. 2, bottom).

3.1.2. Ecosystem service classification differs in U.S. and EU

Beyond the maturity and completeness of the accounts themselves, the EU and U.S. special issue papers took different approaches to ecosystem service classification. The Common International Classification of Ecosystem Services (CICES, Haines-Young and Potschin, 2018) is endorsed by the European Environment Agency while the National Ecosystem Services Classification System (NESCS, U.S. EPA, 2015, Newcomer-Johnson et al., 2020) has been developed by the U.S. Environmental Protection Agency. CICES is a hierarchical list of ecosystem services that builds on past ecosystem service typologies while NESCS classifies services as the combination of an end-product produced by a specific ecosystem and used by a specific economic entity (NESCS can thus theoretically produce thousands of possible ecosystem service combinations). Although different in approach, CICES and NESCS can be framed as complementary, especially when building on the strengths of the two classification systems (La Notte and Rhodes, 2020). As an example of the implications of choice of classification system, "crop provision" and "timber provision" are treated as services by European accounts (Hein et al., 2020b, Vallecillo et al., 2020) while NESCS and the recent SEEA EA revision (United Nations, 2021a) do *not* consider these to be services, but treat various *ecosystem contributions* toward these economic products as the services.[4] Where biophysical and monetary quantification of final ecosystem contributions indicative of NESCS ecosystem services is not possible due to data limitations, related indicators may still be appropriate for inclusion in ecosystem condition accounts, i.e., as functional state indicators (Maes et al., 2020a). Warnell et al. (2020a) provide examples of such indicators related to wild pollination and water purification, and further discuss these issues in depth and their implications for future SEEA EA applications.

3.1.3. Methodological choices vary in EU and U.S.

As an internationally developed consensus approach, SEEA's conceptual and terminological consistencies promote compatibility with the System of National Accounts and greater comparability of SEEA accounts between nations. SEEA EA accommodated substantial flexibility in approaches during its "experimental" stage (United Nations et al., 2014b, United Nations, 2017); its 2021 revision implies a greater degree of standardization in biophysical accounting while further experimental work remains to be completed on monetary valuation and asset accounts (Edens et al., this issue). Depending on resources, data availability, and the policy priorities accounts seek to inform, countries typically choose which accounting modules to complete rather than completing them all. A variety of approaches are used for SEEA, from biophysical models to "fast-track" methods that use statistical data as proxies and isolate ecosystem contributions to economic products (Cerilli et al., 2020, Hein et al., 2020b, Vallecillo et al., 2020). Biophysical models themselves vary greatly, from country-specific approaches that may be better known and trusted as a result of past use, to off-the-shelf modeling systems with predefined methods and data requirements (e.g., Ecosystem Services Mapping Tool, ESTIMAP, Zulian et al., 2013; Integrated Valuation of Ecosystem Services and Tradeoffs, InVEST, Sharp et al., 2020; Land Utilisation Capability Indicator, LUCI, Jackson et al., 2013) to systems designed to facilitate the interoperability of multiple approaches (e.g., Artificial Intelligence for Environment and Sustainability, ARIES, Villa et al., 2014). Houdet et al. (2020), and Ingram et al. (this issue) both note that the lack of comprehensive data at relevant spatial and temporal scales is a challenge for businesses' use of NCA data. Emissions and materials use are more consistently reported by companies, but site-scale impacts, e.g., to biodiversity, are not (Houdet et al., 2020). Houdet et al., thus develop an approach to do so and the potential for integration with SEEA information.

3.2. Key commonalities between U.S. and EU NCA applications

3.2.1. NCA applications use diverse data sources

Both the U.S. and EU benefit from a mature landscape for scientific data and models relative to much of the rest of the world. The role of data in the statistical system is changing from traditional data sources collected using questionnaires to a greater emphasis on the use of data from remote sensing platforms, volunteered data, and data generated by the scientific community and private sector. For instance, the U.S. land accounts relied heavily on data from a private company, Zillow, which provided a database of 374 million property transactions to underpin national-scale land valuation (Wentland et al., 2020). Crowdsourced data also have a growing role in ecosystem accounts, for example, in the use of multiple forms of volunteered and social media data in a pilot study for the Netherlands (Havinga et al., 2020b) and in providing recreational birdwatching data for ecosystem accounts in the U.S. Southeast (Warnell et al., 2020a). Finally, the special issue papers that used modeling rely on Earth observation data, whose content and variety are growing rapidly. Efforts are underway in the EU (Eionet, 2018) and worldwide (EO4EA, 2020) to better link the Earth observation and ecosystem accounting communities, supporting ecosystem accounting through better and more timely data.

3.2.2. Despite data abundance, key gaps exist for U.S. And EU NCA

NCA data gaps remain even in the relatively data-abundant EU and U.S., though they may be fewer in nations with a long history of collecting environmental statistics, like the Netherlands. For instance, spatial data on beneficiaries have long been a limiting factor in ecosystem service assessments and accounting, particularly for understanding ecosystem service demand and allowing for the quantification of flows (Tashie and Ringold, 2019). The U.S. National Land Use Database, produced at 30 m resolution (Theobald, 2014), allows much finer classification of users in SEEA use tables than most previous accounting studies have allowed (e.g., Heris et al., 2021; Wentland et al., 2020). However, it is not produced under the umbrella of a government agency nor with a well-defined update plan. Institutionally supported products provide a degree of security to account developers and users that comparable needed time series will be available in the future. This increases the usability of data products, both for practitioners wanting to conduct time-series analysis, but also for those planning to make decisions explicitly based on the data who need assurance that data products will be consistent and updated over time.

3.2.3. NCA can address multiple scales; scale of analysis matters but data limitations can hinder compilation of accounts at some useful scales

Papers in the special issue illustrate the wide range of spatial scales over which natural capital accounts may be compiled—from the supranational to the project scale (Table 1). When assessing change for large entities like the EU and U.S., substantial change may not be visible at national or supranational scales, but important trends emerge when results are summarized locally. For instance, Petersen et al. (this issue) and Wentland et al. (2020) both note relatively little change in EU

[4] The EU papers generally acknowledge this point and use modeling to quantify relevant ecosystem contributions (Vallecillo et al., 2020) but leave crop and timber production as ecosystem service labels in their supply and use tables. Croplands and forests of course provide other ecosystem services as well, which are quantified in supply and use accounts.

ecosystem extent and U.S. land accounts, respectively, but quantify meaningful sub-national trends. Similarly, Warnell et al. (2020a), note limited change in ecosystem condition and services across a nearly 1.4 million km^2 10-state region of the U.S. However, they found more rapid, interconnected changes in land, water, ecosystem, and economic accounts in a fast-growing 29-county region around metropolitan Atlanta, which more fully show linked trends between the environment and economy. Additionally, Vallecillo et al. (2020) reported small changes in EU-level ecosystem service flows, while country-level results show better-defined trends (Vallecillo et al., 2018 and Vallecillo et al., 2019 report country-level accounting tables).

Data limitations may hinder the development of useful NCA information for two scales useful for decision-making—watersheds and supply chains. The problem of disaggregating statistical data across biophysical regions like watersheds or ecoregions is a well-known issue for water accounts (Bagstad et al., 2020a). Although biophysical models typically produce raster (grid-based) outputs that can be flexibly aggregated using diverse ecosystem accounting areas, data obtained through surveys are typically collected for administrative units that may be difficult to reaggregate to watershed or ecoregional boundaries. In private-sector NCA, businesses operate at the scale of supply chains, which are typically international and do not easily map into spatial units (Hein et al., 2020b, Ingram et al., this issue). By accounting for imports and exports, Cerilli et al. (2020) illustrate how NCA could better account for supply chains.

3.2.4. Simple models may be inadequate in the U.S. and EU

The relative abundance of scientific expertise in the EU and U.S. raises the question of how acceptable simple or generalized models will be to U.S. and EU scientific and policy communities relative to more complex (and potentially realistic) approaches. Simple models can be useful for more rapidly developing pilot accounts that track changes over time and enable comparison of trends between ecosystem services; as such, uncalibrated InVEST sediment regulation models were deemed acceptable in SEEA EA accounts for Rwanda (Republic of Rwanda, 2019). In the U.S., such approaches are unlikely to be considered adequate given the decades of development of more advanced water quality models (e.g., Spatially Referenced Regression on Watershed attributes, SPARROW, Schwarz et al., 2006). In more advanced EU cases, the complexity and accuracy of models differs substantially between services, from simple to complex (Hein et al., 2020b, Vallecillo et al., 2020). As a complex model example, the Geospatial Regression Equation for European Nutrient losses (GREEN) model, which is analogous to SPARROW, was used for modeling EU nutrient regulation in the SEEA EA (La Notte et al., 2017a). A higher scientific bar for developing rigorous and policy-relevant accounts in data-abundant environments poses challenges in nations like the U.S. that are earlier in their SEEA accounts development. A related issue surrounds the importance of using "best available" data and models, and is illustrated in the EU by the simultaneous compilation of supranational- and national-scale accounts, where national-scale accounts may use finer-grained data and more nuanced methods than supranational accounts (Hein et al., 2020b). Further assessment of the added value of using simpler versus more complex models and local versus national, supranational, or global data will be beneficial in informing future SEEA EA account efforts (e.g., Bagstad et al., 2018). Finally, comparisons between different land cover datasets may be useful to reduce uncertainty in SEEA land cover change analyses (La Notte et al., 2017b).

3.2.5. Centralized, replicable data and model management strategies are needed

Since ecosystem accounts need to be recompiled as new data become available in order to develop continuous time series, viable long-term data and model management strategies are important. Both the institutional home of the data and the ability to recompile accounts using the same methods and models must be consistent. Data harmonization is particularly important in supranational accounting for the EU: Regulation (EU) 691/2011 provides a legal framework for a harmonized collection of comparable data from all EU Member States plus Iceland, Liechtenstein, and Norway (the European Economic Area). These environmental accounts are consistent with the SEEA CF and are structured in modules. This legislation may be amended in the future with a module on ecosystem accounts. The U.S. is at an earlier stage of the process, but recent U.S. urban ecosystem accounts have developed a public code repository for the underlying models, which can be rerun by a skilled Python programmer (Heris et al., 2021; the U.S. approach has also been tested in the EU). The code has been parallelized to support its use across large geographic areas, and a similar approach is underway in producing national-scale pollination accounts for the U.S. Input and output data have also been placed in public repositories (Warnell et al., 2020b). By contrast, the southeastern U.S. accounts (Warnell et al., 2020a) took a faster but less replicable approach to accounts development, soliciting the active participation and data sharing of different modelers for different ecosystem services. There is no guarantee that when accounts need to be updated in future years, the various models' code will be kept up to date or that all past participants will contribute results in the future. This "kindness of strangers" approach, where account developers ask different research groups to contribute results for different ecosystem service accounts, is appealing for the development of pilot accounts, but is not likely to be sustainable without official buy-in.

The Mapping and Assessment for Integrated ecosystem Accounting (MAIA) project (MAIA, 2020) is working with 10 EU countries[5] to test, pilot, and mainstream current and innovative approaches for NCA. In its initial experimental phase, this approach can be useful in identifying the best modeling options. However, once a reasonably stable knowledge base is agreed upon (i.e., a set of models that rely on the same group of variables), the experimental approach should ideally evolve toward more stable implementation toolkits, with the possibility of longer-term improvements and enhancements. A recently released SEEA platform built on ARIES (Villa et al., 2014, United Nations, 2021b) offers a path toward increased interoperability and reusability of SEEA data and models, building on the FAIR principles for scientific data (Findable, Accessible, Interoperable, Reusable; Wilkinson et al., 2016). The ARIES for SEEA application thus provides a platform for data and model interoperability that enables the rapid compilation of ecosystem accounts anywhere on Earth while also automating the model customization process in data-abundant environments (Martínez-López et al., 2019). This is particularly important in countries where capacity to develop accounts is limited (Brandon et al., 2021).

3.2.6. NCA benefits from best practices in ecosystem service modeling, but these practices are not always followed

Four additional methodological considerations are raised by papers in the special issue. First, uncertainty analyses are useful in SEEA accounts, particularly as statistical offices begin to more widely use geospatial data and biophysical models as critical tools to develop natural capital accounts. Petersen et al. (this issue) provide thresholds for considering the uncertainty of land cover and ecosystem change in the EU, which are useful when considering whether observed land and ecosystem extent changes represent real trends or data artifacts. Heris et al., 2021, provide uncertainty estimates for U.S. urban ecosystem accounts, using error propagation and reporting confidence intervals for modeled SEEA EA accounts. Second, model customization is particularly important in quantifying ecosystem services for large, biophysically and socioeconomically heterogeneous regions like the U.S. and the EU. For example, Heris et al. (2021) built city-specific multivariate regression models that underpin urban heat island models for over 700 U.S. cities. Machine learning is one approach to model customization; it is

[5] Countries participating in MAIA include Belgium, Bulgaria, Czechia, Finland, France, Germany, Greece, the Netherlands, Norway, and Spain.

increasingly used in ecosystem services modeling (Willcock et al., 2018, Havinga et al., 2020a) and will likely be useful in future SEEA EA applications. Third, quantifying the actual or realized use of an ecosystem service (i.e., actual ecosystem service flows) and reporting it in the supply and use table still remains a conceptual and methodological challenge, particularly for regulating ecosystem services (Vallecillo et al., 2020). Models are needed that better integrate the key drivers of actual ecosystem service flows, including how much and where ecosystems produce goods and services that may be useful to society, and how and where society uses them. Fourth, official statistics can be combined with other spatial data to produce proxies for SEEA EA account entries, particularly for provisioning services such as biomass provisioning (e.g., timber and crops). However, further analysis is typically needed to quantify ecosystem contributions to timber and crop production (Vallecillo et al., 2020) in ways that can assess sustainability of natural capital use (Cerilli et al., 2020).

3.2.7. *Spatiotemporal resolution and data latency for accounts are good in the U.S. and EU, but challenges remain*

As relatively data-abundant environments, most U.S. and EU accounts were compiled at relatively high spatial resolution. U.S. accounts were generally completed at 30 m resolution, reflecting the frequent use of Landsat-derived data inputs. Some European accounts were completed at coarser resolution (i.e., 1 km, Capriolo et al., 2020, Petersen et al., this issue) while some for the Netherlands were developed at higher resolution (i.e., 10 m, Hein et al., 2020b). The chosen spatial resolution largely depends on data availability; for instance, the resolution of accounts developed by Vallecillo et al. (2020) varied when the modeling approach was driven by statistical data or remote sensing-derived products. Sensitivity analyses have shown which ecosystem services and environments require higher resolution to maintain accuracy; notable models sensitive to changes in spatial resolution include hydrologic models and those run in heterogeneous environments like cities, small farms, and areas of high topographic relief (Bagstad et al., 2018). In the Netherlands, a small nation with heterogeneous land cover, high-resolution data have been used in their current and past ecosystem accounts (Hein et al., 2020b). Similarly, Heris et al. (2021), quantified the relatively high uncertainty introduced by using 30 m tree canopy cover data with ecosystem service models in cities; however, lacking higher-resolution national data, national-scale urban ecosystem accounts must currently accept this limitation. The recent availability of free 10–20 m resolution Sentinel data is useful for NCA, but lacks the historical archives of other data products e.g., from Landsat, Moderate Resolution Imaging Spectroradiometer (MODIS, NASA, 2020), or the Copernicus Global Land Service archives (Copernicus Global Land Service, 2020)—a tradeoff that will be important for NCA practitioners to navigate.

In addition, temporal aspects are critical to NCA, including the length of the time series, latency (time to production in terms of number of months or years needed to release results for a given year), and number of years included within each accounting period (e.g., annual or every five years). Studies in this special issue covered an average of 9.3 years, with coverage as long as 18 years (Petersen et al., this issue) and at minimum a single year (Capriolo et al., 2020, Cerilli et al., 2020; Table 1). None of the studies included data from before the year 2000. Generally, of course, accounts with longer time series, short latency, and multiple accounting periods are desirable but data availability frequently constrains one or more of these temporal aspects. Short latency is particularly important when using accounts in decision making, where having up-to-date information can be critical (i.e., all else being equal, 2019 data are better than 2015 data for a decision in 2020), and data must be delivered in time to support decisions being made. This is particularly true for the ability of the private sector to use NCA data, given their emphasis on quarterly reporting and strategic planning, which may align to roughly three- to five-year time scales (Ingram et al., this issue).

Underlying data—whether statistical data for “fast-track” accounts or modeled data—affect the frequency with which accounts can be compiled. In some cases, when the change in ecosystem service flows depends on extraction (e.g., timber and fish provision) or absorption (e.g., water purification, carbon sequestration, and air filtration), quantification of annual flows is useful to closely track natural capital trends. In other cases, when driven by land-use change, accounts can be measured across intervals longer than one year (particularly in slow-changing environments or when annual crop rotation cycles would add unhelpful noise to long-term trends). Similarly, for accounts dependent on annual weather patterns, it may be useful to use multiyear weather data or to hold weather data constant between years to isolate the effects of ecosystem change on service provision (Heris et al., 2021, Warnell et al., 2020a; varying temporal approaches are explained in more details in La Notte et al., 2019a). It is valuable in such cases to understand model sensitivity to different inputs (e.g., weather vs. land use/land cover).

For European accounts, land use-land cover reference data (i.e., Coordination of Information on the Environment, CORINE, Copernicus Program, 2020) are available every six years (2000, 2006, 2012, 2018), so if the compilation of accounts is based on CORINE, it will thus inevitably follow the same temporal sequence. However, ancillary data used to model ecosystem services do not necessarily match the same years, and the best correspondence between available years must be found. For instance, crop distribution data for pollination accounts were only available for 2004 and 2008 (Vallecillo et al., 2020). In this sense, integration of different datasets with varying years, thematic purposes, and spatial resolution is another key challenge. In the U.S., the National Land Cover Dataset (NLCD) provides time series data on land cover, tree canopy, and impervious surfaces, and is produced every five years (2001, 2006, 2011, 2016, Yang et al., 2018), with land cover also included in interim years (2004, 2008, 2013, 2019). A new USGS product, LCMAP, now provides annual 30 m U.S. land cover data for the years 1985–2019 but with fewer land cover classes than NLCD (Brown et al., 2020). This dataset is worth investigation in future U.S. NCA, particularly for its ability to provide an annual 30+ year time series. Similar data latency and gap issues exist for U.S. water-use data, which have been compiled every five years since 1950, with a several-year gap before publication (Bagstad et al., 2020a). However, the compilation of U.S. water accounts helped bring added visibility to this problem, leading to funding for a new working group tasked with producing water-use data on a monthly to seasonal basis with minimal latency (USGS Powell Center, 2020).

4. Conclusions

Papers in the special issue identify key NCA similarities, differences, and needs for the EU, U.S., and more broadly, including data and scientific needs that may inform future evolution of the SEEA and next-generation EU and U.S. accounts. While NCA efforts in the EU and U.S. use distinct data and methods, methodological convergence (while allowing national-scale flexibility) is a useful long-term goal to facilitate international comparisons used in, for example, wealth accounts (Lange et al., 2018, UNEP, 2018) or the EU's supranational accounts. Additionally, lessons learned can help to expand the use of NCA elsewhere (Table 3). Past SEEA EA applications have spanned the developing and developed world (Hein et al., 2020a). By drawing on growing global NCA experience, additional nations may be able to apply methods used in the U.S. and EU, including fast-track statistical approaches and spatial models as well as emerging approaches like ARIES for SEEA (see Section 3.2.3; United Nations, 2021b).

The U.S. and EU have different NCA needs, which arise in part due to their different stages of accounts' development. EU organizations have been developing accounts for years and have been given mandates to do so. EU institutions and scientists will consequently continue to expand the depth, breadth, and temporal coverage of EU accounts. The U.S. is at an earlier stage of accounts development but has the data to build many new accounts, particularly if demonstrated demand exists. NCA demand will likely increase as accounts are consolidated and clear examples emerge of how NCA improves policymaking. First-generation U.S. accounts, as well as EU accounts, mention the need to improve their timeliness, completeness (in terms of both the number of services and the inclusion of ecosystem condition, physical and monetary supply and use accounts, and asset accounts, see Section 1), and quality across various dimensions. The need for wider dissemination of the accounts to build public awareness and their use in decision making (see Section 2) is also generally noted in the U.S. accounts papers. SEEA in particular provides a structured means for answering past calls to more systematically quantify the condition of U.S. ecosystems and the services they provide to society (Heinz Center, 2008, Jackson et al., 2016); EU NCA efforts have recently enabled such systematic ecosystem assessments for Europe (Maes et al., 2020b). EU accounts provide novel contributions including the linkage between SEEA Agriculture, Forestry and Fisheries accounts and SEEA EA (Cerilli et al., 2020), ecosystem extent accounts (Petersen et al., this issue), and calculations for estimating ecosystem service flows and unmet demand (Vallecillo et al., 2020). These analyses can be conducted on a more widespread level, along with calculations of additional measurement concepts like capacity, which is recognized as important but has relatively few worked examples (Hein et al., 2016; La Notte et al., 2019b). EU accounts also call for improved data (Petersen et al., this issue; Vallecillo et al., 2020; Cerilli et al., 2020), methods, and assumptions underlying monetary valuation (Capriolo et al., 2020; Hein et al., 2020b).

The recent SEEA EA revision process has substantially strengthened SEEA's conceptual and theoretical foundation, particularly for ecosystem extent, condition, and physical supply and use accounts (Edens et al., this issue, U.N. 2021). However, key methodological and data gaps remain. For example, none of the papers in this special issue address ocean NCA, a critical and acknowledged gap (Fenichel et al., 2020) for which pilot accounts are beginning to be constructed (Global Ocean Accounts Partnership, 2020). The difficulty of quantifying other hard-to-measure natural capital assets like groundwater (and the sustainability of its use) at national scales is also acknowledged (Bagstad et al., 2020a). For private-sector NCA, (Houdet et al., 2020), and Ingram et al., this issue highlight data needs that, if filled, could help make private-sector use of national-scale NCA data more rigorous and decision relevant. Most notably, substantial experimental work remains to be done to develop NCA-compatible approaches for national-scale monetary valuation (Brown et al., 2021). Although four of the special issue papers included valuation information (Capriolo et al., 2020; Hein et al., 2020b; Heris et al., 2021; Vallecillo et al., 2020), data scarcity and methodological consistency remain significant challenges for valuation (Brandon et al., 2021).

SEEA accounts notably require partnerships between statistical and science agencies and ideally close communication with users, in order to understand and be responsive to user needs in developing decision-relevant accounts and indicators (Fig. 2). In addition to national-scale collaborations, various global communities of practice have been critical to NCA's growth. These include the World Bank's Wealth Accounting and Valuation of Ecosystem Services/Global Program on Sustainability (WAVES/GPS), the U.N. Statistics Division's coordination of new technical guidance and standards, and Group on Earth Observations initiatives like Earth Observation for Ecosystem Accounting (EO4EA). New applications of the SEEA and the collaborations needed to build and strengthen these efforts help to grow national and regional expertise that can benefit SEEA development elsewhere in the world. A variety of technical solutions are often proposed to improve the ease of compiling accounts, such as more widespread use of Earth observation, crowdsourced, and other types of data; machine learning; and cloud-based platforms to improve data and model interoperability and reuse (Hein et al., 2020a). All of these will require greater coordination and in some cases community buy-in, making international communities of practice critical for advancing NCA's development and use.

SEEA EA has inherent limitations related to the scope of valuation (imposed to ensure compatibility with the System of National Accounts) and the relative difficulty in handling complexity and uncertainty inherent in ecological systems (Hein et al., 2020b; Brandon et al., 2021). While NCA can track trends in stocks of or flows from natural capital over time for certain regions, accounts are unlikely to provide sufficient information to tell us how close we are to crossing ecological thresholds or exceeding planetary boundaries (i.e., Steffen et al., 2015; O'Neill et al., 2018; IPBES, 2019). Related limitations include (1) the incompleteness of accounts in terms of the number of condition indicators and services assessed, and the related challenge of comprehensively valuing ecosystem assets, (2) short time series (no accounts in the special issue go back earlier than 2000, and the average length of time covered by its quantitative accounts was 9.3 years), and (3) incompletely quantified effects of trade through both indirectly traded natural resources (e.g., virtual water, D'Odorico et al., 2019) and "offshoring" of environmental burdens by developed nations (Oleson, 2011, Helm, 2019, Marques et al., 2019, Kleemann et al., 2020). The third limitation is particularly relevant, given high consumption levels in the U.S. and EU, which can have significant local environmental impacts on nations exporting to the U.S. and EU (Fuchs et al., 2020). These impacts are often challenging to systematically quantify and have to date seen limited treatment using SEEA EA. Together, these three factors currently limit SEEA's ability to comprehensively track sustainability.

When informing decision making, NCA results should be analyzed at the appropriate scale. Such analyses can best consider the context of local management practices, societal demands, and future scenarios. Several papers in this special issue note that while change across large geographic areas may appear small, local-scale analysis can reveal important trends (Petersen et al., this issue; Warnell et al., 2020a; Wentland et al., 2020). Modeled SEEA EA results can typically be aggregated at various scales, but limitations may exist when disaggregating statistical data reported by administrative divisions across biophysical boundaries like watersheds (Bagstad et al., 2020a), and in assessing supply chains in private-sector accounts (Houdet et al., 2020, Ingram et al., this issue).

The science and practice of NCA has advanced rapidly in the last decade. While important limitations remain, this special issue shows how various approaches can improve reporting on natural capital for public and private sector uses. Collaborations between natural scientists, economists, and accountants can help to address NCA's underlying scientific and data challenges, while governmental, NGO, and private-sector collaboration can advance NCA's usefulness for decision making. All such collaborations improve both the "accounting push" and "policy pull" for NCA (Vardon et al., 2016). Taken together, such efforts maximize the opportunity for NCA to live up to its billing—improved management of both the economy and ecosystems on which humanity depends (Gleeson-White, 2015).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Anderson, H., 2018. U.K. natural capital: Ecosystem accounts for urban areas. Office of National Statistics. Accessed September 30, 2020 from: https://www.ons.gov.uk/releases/uknaturalcapitalecosystemaccountsforurbanareas.

Bagstad, K.J., Ancona, Z.H., Hass, J., Glynn, P.D., Wentland, S., Vardon, M., Fay, J., 2020a. Integrating physical and economic data into experimental water accounts for the United States: lessons and opportunities. Ecosystem 45, 101182.

Bagstad, K.J., Cohen, E., Ancona, Z.H., McNulty, S.G., Sun, G.e., 2018. The sensitivity of ecosystem service models to choices of input data and spatial resolution. Appl. Geogr. 93, 25–36.

Bagstad, K.J., Ingram, J.C., Lange, G.-M., Masozera, M., Ancona, Z.H., Bana, M., Kagabo, D., Musana, B., Nabahungu, N.L., Rukundo, E., Rutebuka, E., Polasky, S., Rugege, D., Uwera, C., Buckley, Y., 2020b. Towards ecosystem accounts for Rwanda: tracking 25 years of change in flows and potential supply of ecosystem services. People Nat. 2 (1), 163–188.

Banerjee, O., Bagstad, K.J., Cicowiecz, M., Dudek, S., Horridge, M., Alavalapati, J.R.R., et al., 2020. Economic, land use, and ecosystem services impacts of Rwanda's Green Growth Strategy: an application of the IEEM+ESM Platform. Sci. Total Environ. 729, 138779.

Boyd, J.W., Bagstad, K.J., Ingram, J.C., Shapiro, C., Adkins, J.E., Casey, F., et al., 2018. The Natural Capital Accounting opportunity: let's really do the numbers. BioScience 68 (12), 940–943.

Brandon, C., Brandon, K., Fairbrass, A., Neugarten, R., 2021. Integrating natural capital into national accounts: three decades of promise and challenge. Rev. Environ. Econ. Policy 15 (1), 134–153.

Brown, J.F., Tollerud, H.J., Barber, C.P., Zhou, Q., Dwyer, J.L., Vogelmann, J.E., et al., 2020. Lessons learned implementing an operational continuous United States national land change monitoring capability: The Land Change Monitoring, Assessment, and Projection (LCMAP) approach. Remote Sens. Environ. 238, 111356.

Brown, N., Femia, A., Fixler, D., Gravgård Pedersen, O., Kaumanns, S.C., Oneto, G.P., Schürz, S., Tubiello, F.N., Wentland, S., 2021. Statistics: unify ecosystems valuation. Nature 593 (7859), 341.

Burkhard, B., Maes, J., Potschin-Young, M.B., Santos-Martín, F., Geneletti, D., Stoev, P., et al., 2018. Mapping and assessing ecosystem services in the EU – lessons learned from the ESMERALDA approach of integration. One Ecosystem 3, e29153.

Capitals Coalition. 2020. Combining Forces on Natural Capital. Accessed November 18, 2020 from: https://naturalcapitalcoalition.org/projects/combining-forces-on-natural-capital/.

Capriolo, A., Boschetto, R.G., Mascolo, R.A., Balbi, S., Villa, F., 2020. Biophysical and economic assessment of four ecosystem services for natural capital accounting in Italy. Ecosyst. Serv. 46, 101207.

Carson, C.S., 1995. Integrated economic and environmental satellite accounts. Nonrenewable Resour. 4 (1), 12–33.

Cerilli, S., La Notte, A., Pisani, D., Vallecillo, S., Tubiello, F.N., 2020. A sustainability scoreboard for crop provision in Europe. Ecosyst. Serv. 46, 101194.

Copernicus Global Land Service. 2020. Overview of the product portfolio. Accessed July 30, 2020 from: https://land.copernicus.eu/global/products/.

Copernicus Program. 2020. CORINE land cover. Accessed September 30, 2020 from: https://land.copernicus.eu/pan-european/corine-land-cover.

D'Odorico, P., Carr, J., Dalin, C., Dell'Angelo, J., Konar, M., Laio, F., et al., 2019. Global virtual water trade and the hydrologic cycle: patterns, drivers, and socio-environmental impacts. Environ. Res. Lett. 14 (5), 053001.

Dvarskas, A., 2019. Experimental ecosystem accounting for coastal and marine areas: a pilot application of the SEEA-EEA in Long Island coastal bays. Marine Policy 100, 141–151.

Earth Observation for Ecosystem Accounting (EO4EA). 2020. Accessed July 29, 2020 from: https://www.eo4ea.org/.

Edens, B., J. Maes, L. Hein, C. Obst, J. Siikamaki, S. Schenau, et al. This issue. Standardizing the framework for ecosystem accounting. Ecosystem Services.

Eionet. 2018. Earth observation data for ecosystem accounting: Material to support the GEO EO4EA Initiative. Accessed July 29, 2020 from: https://projects.eionet.europa.eu/ecosystem-capital-accounting/library/earth-observation-data-ecosystem-accounting.

European Commission. 2011a. Regulation (EU) No 691/2011 of the European Parliament and of the Council of 6 July 2011 on European environmental economic accounts.

European Commission. 2011b. Our life insurance, our natural capital: An EU biodiversity strategy to 2020. COM(2011) 244 final Accessed September 30, 2020 from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0244&from=EN.

European Court of Auditors. 2019. European Environmental Economic Accounts: usefulness for policymakers can be improved. Special report number 16. doi: 10.2865/06806.

European Environment Agency (EEA). 2013. Results and lessons from implementing the Water Asset Accounts in the EEA area: From concept to production. EEA Technical Report No. 7/2013. Luxembourg: Publications Office of the European Union.

European Environment Agency (EEA). 2019. Natural capital accounting in support of policymaking in Europe. EEA Report No. 26/2018. Luxembourg: Publications Office of the European Union.

Eurostat. 2020. Environment – overview. Accessed November 17, 2020 from: https://ec.europa.eu/eurostat/web/environment/overview.

Fenichel, E.P., Abbott, J.K., Bayham, J., Boone, W., Haacker, E.M.K., Pfeiffer, L., 2016. Measuring the value of groundwater and other forms of natural capital. Proc. Natl. Acad. Sci. 113 (9), 2382–2387.

Fenichel, E.P., Addicott, E.T., Grimsrud, K.M., Lange, G.-M., Porras, I., Milligan, B., 2020. Modifying national accounts for sustainable ocean development. Nat. Sustainability 3 (11), 889–895. https://doi.org/10.1038/s41893-020-0592-8.

Finisdore, J., Rhodes, C., Haines-Young, R., Maynard, S., Wielgus, J., Dvarskas, A., et al., 2020. The 18 benefits of using ecosystem services classification systems. Ecosyst. Serv. 45, 101160.

Fuchs, R., Brown, C., Rounsevell, M., 2020. Europe's Green Deal offshores environmental damage to other nations. Nature 586 (7831), 671–673.

Gleeson-White, J., 2015. Six capitals, or can accountants save the planet?: Rethinking capitalism for the twenty-first century. W.W. Norton, New York.

Global Ocean Accounts Partnership. 2020. Accessed August 3, 2020 from: https://www.oceanaccounts.org/.

Green Growth Knowledge Partnership. 2020. Practical policy use cases for natural capital information: A review of evidence for the policy relevance and impact of natural capital information. Geneva: Green Growth Knowledge Partnership.

Havinga, I., Hein, L., Vega-Araya, M., Languillaume, A., 2020a. Spatial quantification to examine the effectiveness of payments for ecosystem services: a case study of Costa Rica's Pago de Servicios Ambientales. Ecol. Ind. 108, 105766.

Havinga, I., Bogaart, P.W., Hein, L., Tuia, D., 2020b. Defining and spatially modelling cultural ecosystem services using crowdsourced data. Ecosyst. Serv. 43, 101091.

Haines-Young, R., Potschin, M., 2018. Common International Classification of Ecosystem Services (CICES) v5.1: Guidance on the application of the revised structure. Fabis Consulting, Nottingham, U.K. Accessed September 30, 2020 from: https://cices.eu/content/uploads/sites/8/2018/01/Guidance-V51-01012018.pdf.

Hein, L., Bagstad, K.J., Edens, B., Obst, C., de Jong, R., Lesschen, J.P., 2016. Defining Ecosystem Assets for Natural Capital Accounting. PLOS One 11 (11), e0164460.

Hein, L., Bagstad, K.J., Obst, C., Edens, B., Schenau, S., Castillo, G., Soulard, F., Brown, C., Driver, A., Bordt, M., Steurer, A., Harris, R., Caparrós, A., 2020a. Progress in natural capital accounting for ecosystems. Science 367 (6477), 514–515.

Hein, L., Remme, R.P., Schenau, S., Bogaart, P.W., Lof, M.E., Horlings, E., 2020b. Ecosystem accounting in the Netherlands. Ecosyst. Serv. 44, 101118.

Heinz Center, 2008. State of the Nation's Ecosystems 2008: Measuring the land, waters, and living resources of the United States. Island Press, Washington, DC.

Helm, D., 2019. Natural capital: Assets, systems, and policies. Oxford Rev. Econ. Policy 35 (1), 1–13.

Heris, M., Bagstad, K.J., Rhodes, C., Troy, A., Middel, A., Hopkins, K.G., et al., 2021. Piloting urban ecosystem accounting for the United States. Ecosyst. Serv. 48, 101226.

Highfill, T., Smith-Nelson, C., 2018. Outdoor Recreation Satellite Account Methodology. US Bureau of Economic Analysis. Accessed September 30, 2020 from: https://www.bea.gov/system/files/methodologies/Outdoor%20Recreation%20Satellite%20Account%20Methodology_0.pdf.

Hoekstra, R., 2019. Replacing GDP by 2030: Towards A Common Language for the Well-being and Sustainability Community. Cambridge University Press, Cambridge.

Horlings, E., S. Schenau, L. Hein, M. Lof, L. de Jongh, Polder, M., 2020. Experimental monetary valuation of ecosystem services and assets in the Netherlands. Accessed June 2, 2021 from: https://www.cbs.nl/en-gb/background/2020/04/monetary-valuation-of-ecosystem-services-for-the-netherlands.

Houdet, J., Ding, H., Quétier, F., Addison, P., Deshmukh, P., 2020. Adapting double-entry bookkeeping to renewable natural capital: an application to corporate net biodiversity impact accounting and disclosure. Ecosyst. Serv. 45, 101104.

Ingram, J.C., K.J. Bagstad, M. Vardon, C. Rhodes, S. Posner, C.F. Casey, et al. This issue. The importance of natural capital accounting for business applications in the United States. Ecosystem Services.

IPBES, 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany.

Jackson, B., Pagella, T., Sinclair, F., Orellana, B., Henshaw, A., Reynolds, B., et al., 2013. Polyscape: a GIS mapping framework providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services. Landscape Urban Plann. 112, 74–88.

Jackson, S.T., Duke, C.S., Hampton, S.E., Jacobs, K.L., Joppa, L.N., Kassam, K.-A., et al., 2016. Toward a national, sustained U.S. ecosystem assessment. Science 354 (6314), 838–839.

Kleemann, J., Schröter, M., Bagstad, K.J., Kuhlicke, C., Kastner, T., Fridman, D., et al., 2020. Quantifying interregional flows of multiple ecosystem services—a case study for Germany. Global Environ. Change 61, 102051.

La Notte, A., 2018. Accounting for the ecosystem services generated by Nature-based Solutions to measure urban resilience. A methodological proposal. Economics and Policy of Energy and the Environment 2/2018:43-61.

La Notte, A., Maes, J., Dalmazzone, S., Crossman, N.D., Grizzetti, B., Bidoglio, G., 2017a. Physical and monetary ecosystem service accounts for Europe: a case study for in-stream nitrogen retention. Ecosyst. Serv. 23, 18–29.
La Notte, A., Marques, A., 2017. The role of enabling actors in ecosystem service accounting. One Ecosyst. 2, e20834.
La Notte, A., A. Marques, D. Pisani, S. Cerilli, S. Vallecillo, C. Polce, et al. 2020. Linking accounts for ecosystem service and benefits to the economy through bridging (LISBETH): Natural capital accounts and economic models: Interactions and applications. Publications Office of the European Union: Luxembourg. Accessed September 30, 2020 from: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC120571/jrc_report_lisbeth_final_1.pdf.
La Notte, A., Rhodes, C., 2020. The theoretical frameworks behind integrated environmental, ecosystem, and economic accounting systems and their classifications. Environ. Impact Assess. Rev. 80, 106317.
La Notte, A., Vallecillo, S., Maes, J., 2019a. Capacity as "virtual stock" in ecosystem services accounting. Ecol. Ind. 98, 158–163.
La Notte, A., S. Vallecillo, J. Maes. C. Shapiro, K.J. Bagstad, J.C. Ingram, et al. This issue. Natural capital accounting: The content, the context, and the framework. In review, Ecosystem Services.
La Notte, A., Vallecillo, S., Marques, A., Maes, J., 2019b. Beyond the economic boundaries to account for ecosystem services. Ecosyst. Serv. 35, 116–129.
La Notte, A., S. Vallecillo, C. Polce, G. Zulian, and J. Maes. 2017b. Implementing an EU system of accounting for ecosystems and their services. Initial proposals for the implementation of ecosystem services accounts (Report under phase 2 of the knowledge innovation project on an integrated system of natural capital and ecosystem services accounting in the EU). JRC107150. Accessed December 15, 2020 from: http://publications.jrc.ec.europa.eu/repository/handle/JRC107150?mode=full.
Lange, G., Q. Wodon, and K. Carey (eds.). The Changing Wealth of Nations 2018. The World Bank: Washington, DC.
Maes, J., Driver, A., Czúcz, B., Keith, H., Jackson, B., Nicholson, E., Dasoo, M., 2020a. A review of ecosystem condition accounts: lessons learned and options for further development. One Ecosyst. 5, e53485.
Maes, J., Liquete, C., Teller, A., Erhard, M., Paracchini, M.L., Barredo, J.I., et al., 2016. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. Ecosyst. Serv. 17, 14–23.
Maes, J., Teller, A., Erhard, M., Conde, S., Vallecillo, S., Barredo, J.I., et al., 2020b. Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment. Publication Office of the European Union, Luxembourg.
MAIA. 2020. Mapping and Assessment for Integrated ecosystem Accounting. Accessed July 31, 2020 from: http://www.maiaportal.eu/.
Marques, A., Martins, I.S., Kastner, T., Plutzar, C., Theurl, M.C., Eisenmenger, N., et al., 2019. Increasing impacts of land use on biodiversity and carbon sequestration driven by population and economic growth. Nat. Ecol. Evol. 3 (4), 628–637.
Martínez-López, J., Bagstad, K.J., Balbi, S., Magrach, A., Voigt, B., Athanasiadis, I., Pascual, M., Willcock, S., Villa, F., 2019. Towards globally customizable ecosystem service models. Sci. Total Environ. 650, 2325–2336.
Meagher, L., Lyall, C., 2013. The invisible made visible: Using impact evaluations to illuminate and inform the role of knowledge intermediaries. Evidence Policy 9 (3), 409–418.
NASA. 2020. MODIS data products. Accessed July 30, 2020 from: https://modis.gsfc.nasa.gov/data/dataprod/.
National Research Council, 1999. Nature's Numbers: Expanding the National Economic Accounts to Include the Environment. The National Academies Press, Washington, DC.
Natural Capital Coalition. 2016. The Natural Capital Protocol. Accessed June 2, 2021 from: https://capitalscoalition.org/wp-content/uploads/2021/01/NCC_Protocol.pdf.
Natural Capital Committee. 2013. The State of Natural Capital: Towards a Framework for Measurement and Valuation, First Report to the Economic Affairs Committee, London, Natural Capital Committee.
Natural Capital Coalition. 2020. The Transparent Project. Accessed November 18, 2020 from: https://naturalcapitalcoalition.org/transparent/.
Nature, 2020. New biodiversity targets cannot afford to fail. Nature 578, 337–338.
Newcomer-Johnson, T., F. Andrews, J. Corona, T.H. DeWitt, M.C. Harwell, C. Rhodes, et al. 2020. National Ecosystem Services Classification System (NESCS) Plus. U.S. Environmental Protection Agency. EPA/600/R-20/267.
Nicolls, W., C. Franks, T. Gilmore, R. Goulder, L. Mendelsohn, E. Morgan, et al. 2020. Defining and Measuring the US Ocean Economy. Bureau of Economic Analysis. Accessed September 30, 2020 from: https://www.bea.gov/system/files/2020-06/defining-and-measuring-the-united-states-ocean-economy.pdf.
Obst, C.G., 2015. Reflections on natural capital accounting at the national level: advances in the system of environmental-economic accounting. Sustainab. Account., Manage. Policy J. 6 (3), 315–339.
Obst, C., Vardon, M., 2014. Recording environmental assets in the national accounts. Oxford Rev. Econ. Policy 30 (1), 126–144.
Oleson, K.L.L., 2011. Shaky foundations and sustainable exploiters: problems with national weak sustainability measures in a global economy. J. Environ. Develop. 20 (3), 329–349.
O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustainability 1 (2), 88–95.
Petersen, J.E., E. Mancosu, S. King. This issue. Developing ecosystem extent accounts at European level – Approach and first results. Ecosystem Services.
Republic of Rwanda 2019. Rwanda natural capital accounts – Ecosystems. National Institute of Statistics or Rwanda, Ministry of Finance and Economic Planning, and Ministry of Environment: Kigali. Accessed August 2, 2020 from: https://www.wavespartnership.org/sites/waves/files/kc/Rwanda%20NCA%20Ecosystem%20Accounts%20_Published%20on%203-12-2019.pdf.
Roxburgh, T., K. Ellis, J.A. Johnson, U.L. Baldos, T. Hertel, C. Nootenboom, et al. 2020. Global Futures: Assessing the global economic impacts of environmental change to support policy-making. Summary report, January 2020. Accessed September 30, 2020 from: https://www.wwf.org.uk/globalfutures.
Ruijs, A., Vardon, M., Bass, S., Ahlroth, S., 2018. Natural capital accounting for better policy. Ambio 48, 714–725.
Schwarz, G.E., A.B. Hoos, R.B. Alexander, and R.A. Smith. 2006. The SPARROW Surface Water-Quality Model—Theory, Application and User Documentation: U.S. Geological Survey, Techniques and Methods 6–B3.
Sharp, R., H.T. Tallis, T. Ricketts, A.D. Guerry, S.A. Wood, R. Chaplin-Kramer, et al. 2020. InVEST User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund. Accessed September 30, 2020 from: http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/.
Simões, A., R. Salvador, C. Guedes Soares. 2018. Evaluation of the Portuguese ocean economy using the Satellite Account for the Sea. Pp. 63-68 in: Guedes Soares, C. and T.A. Santos (eds.). Progress in Maritime Technology and Engineering: Proceedings of the 4th International Conference on Maritime Technology and Engineering (MARTECH 2018), May 7-9, 2018, Lisbon, Portugal. CRC Press: Boca Raton, FL.
Smith, R., 2007. Development of the SEEA 2003 and its implementation. Ecol. Econ. 61 (4), 592–599.
Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., et al., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855.
Tashie, A., Ringold, P., 2019. A critical assessment of available ecosystem services data according to the Final Ecosystem Goods and Services Framework. Ecosphere 10 (3), e02665.
Theobald, D.M., 2014. Development and applications of a comprehensive land use classification and map for the US. PLoS ONE 9 (4), e94628.
Tsakiridis, A., M. Aymelek, D. Norton, R. Burger, J. O'Leary, R. Corless, et al. 2019. Ireland's Ocean Economy 2019. Accessed November 17, 2020 from: https://www.nuigalway.ie/media/researchsites/semru/files/Online_Irelands-Ocean-Economy-Report_for-web_final.pdf.
United Nations. 2017. SEEA Experimental Ecosystem Accounting: Technical Recommendations. Accessed September 30, 2020 from: https://seea.un.org/sites/seea.un.org/files/technical_recommendations_in_support_of_the_seea_eea_final_white_cover.pdf.
United Nations. 2020. U.N. SEEA Natural capital and ecosystem services FAQ. Accessed August 18, 2020 from: https://seea.un.org/content/natural-capital-and-ecosystem-services-faq.
United Nations. 2021a. System of Environmental-Economic Accounting—Ecosystem Accounting: Final Draft. March 2021, 362 pp. Accessed June 7, 2021 from: https://unstats.un.org/unsd/statcom/52nd-session/documents/BG-3f-SEEA-EA_Final_draft-E.pdf.
United Nations. 2021b. ARIES for SEEA. Accessed June 3, 2021 from: https://seea.un.org/content/aries-for-seea.
United Nations. 2021c. Guidelines on biophysical modeling for ecosystem services. Accessed June 7, 2021 from: https://seea.un.org/ecosystem-accounting/biophysical-modelling.
United Nations Environment Programme. 2018. Inclusive Wealth Report 2018. Accessed July 30, 2020 from: https://www.unenvironment.org/resources/report/inclusive-wealth-report-2018.
United Nations, European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, and World Bank. 2009. System of National Accounts 2008. (SNA2008) United Nations: New York.
United Nations, European Commission, U.N. Food and Agriculture Organization, International Monetary Fund, Organization for Economic Cooperation and Development, and World Bank. 2014a. System of Environmental-Economic Accounting 2012: Central Framework. Accessed September 30, 2020 from: https://seea.un.org/sites/seea.un.org/files/seea_cf_final_en.pdf.
United Nations, European Commission, U.N. Food and Agriculture Organization, Organization for Economic Cooperation and Development, and World Bank. 2014b. System of Environmental-Economic Accounting 2012: Experimental Ecosystem Accounting. Accessed September 30, 2020 from: https://seea.un.org/sites/seea.un.org/files/seea_eea_final_en_1.pdf.
U.S. Environmental Protection Agency. 2015. National Ecosystem Services Classification System (NESCS): Framework Design and Policy Application. EPA-800-R-15-002. US EPA: Washington, DC. Accessed September 30, 2020 from: https://www.epa.gov/sites/production/files/2015-12/documents/110915_nescs_final_report_-_compliant_1.pdf.
USGS Powell Center. 2020. Reanalyzing and predicting U.S. water use using economic history and forecast data; an experiment in short-range national hydro-economic data synthesis. Accessed September 30, 2020 from: https://www.usgs.gov/centers/powell-ctr/science/reanalyzing-and-predicting-us-water-use-using-economic-history-and?qt-science_center_objects=0#qt-science_center_objects.
Vallecillo, S., La Notte, A., Ferrini, S., Maes, J., 2020. How ecosystems are changing: An accounting application at the EU level. Ecosyst. Serv. 40, 101044.
Vallecillo, S., A. La Notte, G. Kakoulaki, J. Kamberaj, N. Robert, F. Dottori, et al. 2019. Ecosystem services accounting. Part II-Pilot accounts for crop and timber provision, global climate regulation and flood control, EUR 29731 EN, Publications Office of the European Union: Luxembourg. Accessed September 30, 2020 from: http://publications.jrc.ec.europa.eu/repository/handle/JRC116334.
Vallecillo, S., A. La Notte, C. Polce, G. Zulian, N. Alexandris, S. Ferrini, et al. 2018. Ecosystem services accounting: Part I - Outdoor recreation and crop pollination, EUR

29024 EN; Publications Office of the European Union: Luxembourg. Accessed September 30, 2020 from: http://publications.jrc.ec.europa.eu/repository/handle/JRC110321.
Vardon, M. and S. Bass (Eds). 2020. Natural Capital Accounting for Better Policy Decisions: Measuring and Valuing Natural Capital to Improve Landscape Management and Governance. Proceedings and Highlights of the 4th Forum on Natural Capital Accounting for Better Policy Decisions. World Bank WAVES, Washington DC.
Vardon, M., S. Bass, S. Ahlroth (Eds). 2019. Natural Capital Accounting for Better Policy Decisions: Climate change and Biodiversity. Proceedings and Highlights of the 3rd Forum on Natural Capital Accounting for Better Policy Decisions. World Bank WAVES, Washington DC.
Vardon, M., Bass, S., Ahlroth, S., Ruijs, A. (Eds.), 2017. Forum on Natural Capital Accounting for Better Policy Decisions: Taking Stock and Moving Forward. World Bank WAVES, Washington DC.
Vardon, M., Burnett, P., Dovers, S., 2016. The accounting push and the policy pull: balancing environment and economic decisions. Ecol. Econ. 124, 145–152.
Villa, F., Bagstad, K.J., Voigt, B., Johnson, G.W., Portela, R., Honzak, M., et al., 2014. A methodology for adaptable and robust ecosystem services assessment. PLoS ONE 9 (3), e91001.
Virto, L.R., Weber, J.-L., Jeantil, M., 2018. Natural Capital Accounts and public policy decisions: findings from a survey. Ecol. Econ. 144, 244–259.
Vysna V. and A. de la Fuente. 2020. Experience with the implementation of SEEA EEA in the European Union. Conference paper presented at the 26th London Group expert meeting on Environmental Accounting, 5-12 October 2020. Accessed December 16, 2020 from: https://drive.google.com/file/d/1dgYj2iL_PeDMBqJOkik-UvKgTvQruqUc/view.
Vysna, V., J. Maes, J.E. Petersen, A. La Notte, S. Vallecillo, N. Aizpurua, et al. 2021 Accounting for ecosystems and their services in the European Union (INCA). Final report from phase II of the INCA project aiming to develop a pilot for an integrated system of ecosystem accounts for the EU. Statistical report. Publications office of the European Union, Luxembourg.
Warnell, K., M. Russell, C. Rhodes, K.J. Bagstad, L. Olander, D. Nowak, et al. 2020a. Testing ecosystem accounting in the United States: A case study for the Southeast. Ecosystem Services 43:101099.
Warnell, K., M. Russell, C. Rhodes, K.J. Bagstad, L. Olander, D. Nowak, et al. 2020b. Data release for Testing ecosystem accounting in the United States: A case study for the Southeast. U.S. Geological Survey data release, https://doi.org/10.5066/P9MF0K9X.
We Value Nature. 2020. We Value Nature home. Accessed November 19, 2020 from: https://wevaluenature.eu/.
Wentland, S., Ancona, Z., Bagstad, K.J., Boyd, J., Hass, J.L., Gindelsky, M., et al., 2020. Accounting for land in the United States: integrating land cover, land use, and monetary valuation. Ecosyst. Serv. 46, 101178.
Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., et al., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3, 160018.
Willcock, S., Martínez-López, J., Hooftman, D.A.P., Bagstad, K.J., Balbi, S., Marzo, A., et al., 2018. Machine-learning for ecosystem services. Ecosyst. Services 33B, 165–174.
Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S.M., et al., 2018. A new generation of the United States National Land Cover Database: requirements, research priorities, design, and implementation strategies. ISPRS J. Photogramm. Remote Sens. 146, 108–123.
Yang, Y., Ingwersen, W.W., Hawkins, T.R., Srocka, M., Meyer, D.E., 2017. USEEIO: A new and transparent United States environmentally-extended input-output model. J. Cleaner Prod. 158, 308–318.
Yanovitsky, I. and M. Weber. 2020. Conceptual use of research evidence may be more common than you think. Accessed July 13, 2021 from: http://wtgrantfoundation.org/one-more-take-on-the-conceptual-use-of-research-evidence.
Zulian, G., Paracchini, M.-L., Maes, J., Liquete Garcia, M.D.C., 2013. ESTIMAP: Ecosystem Services Mapping at European Scale. Publications Office of the European Union, Luxembourg.