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Cara Steger
Colorado State University

Shana Hirsch
University of Idaho

Cody Evers
Portland State University, cevers@pdx.edu

Benjamin Branoff
University of Puerto Rico-Río Piedras

Maria Petrova
University of Massachusetts Boston

See next page for additional authors

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Authors

Cara Steger, Shana Hirsch, Cody Evers, Benjamin Branoff, Maria Petrova, Max Nielsen-Pincus, Chloe Wardropper, and Carena J. van Riper

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Cara Steger [a,*], Shana Hirsch [b], Cody Evers [c], Benjamin Branoff [d], Maria Petrova [e], Max Nielsen-Pincus [f], Chloe Wardropper [g], Carena J. van Riper [h]

[a] Natural Resource Ecology Lab, Campus Delivery 1499, Colorado State University, Fort Collins, CO 80523-1499, USA
[b] Water Resources Program, 875 Perimeter Drive MS 3002, University of Idaho, Moscow, ID 83844-3002, USA
[c] Department of Environmental Science and Management, Portland State University, PO Box 751, Portland, OR 97207, USA
[d] Department of Biology, University of Puerto Rico-Río Piedras, PO Box 23360, San Juan, PR 00931-3360, Puerto Rico
[e] School for the Environment, University of Massachusetts Boston, 100 Morrissey Blvd, Boston, MA 02125, USA
[f] Department of Environmental Science and Management, PO Box 751, Portland State University, Portland, OR 97207-0751, USA
[g] Department of Forestry and Natural Resources, Purdue University, 195 Marsteller Street, West Lafayette, IN 47907, USA
[h] Department of Natural Resources and Environmental Science, University of Illinois at Urbana-Champaign, 1102 S. Goodwin Ave., Urbana, IL 61801, USA

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ABSTRACT

The ecosystem services (ES) framework has potential to bring transdisciplinary teams together to achieve societal goals. Some label ES as "boundary objects" that help integrate diverse forms of knowledge across social groups and organizational scales. However, this classification masks complexities that arise from unique characteristics of ES types (i.e., provisioning, regulating, and cultural), which influence their ability to function as boundary objects. We argue that interpretive flexibility and material structures interact in distinct ways across ES types throughout a boundary object "life cycle." Viewing a 2015 U.S. federal memorandum as a catalyst, we critically evaluate the evolution of ES and its role as a boundary object. We propose that provisioning and regulating services are transitioning out of boundary object status, moving into a more standardized state. However, we anticipate that cultural services may continue to behave as boundary objects if collaborators maintain them as such. This shift in the functionality of ES as boundary objects is an important consideration for future research that attempts to reach across social worlds and disciplinary perspectives. We urge collaborations to rely on the most relevant disciplinary knowledge, rather than allowing the ease of standardized solutions to dictate the boundary of a given problem.

1. Introduction

The ecosystem services (ES) concept was developed to bridge the natural and social sciences and position ecosystem functions and structures as beneficial to society (Ehrlich and Ehrlich, 1981). This framework provided a common language for communicating across disciplines and increasing public engagement in environmental issues (Braat and de Groot, 2012). Borne from the concern that environmental legislation was increasingly contentious and unable to mitigate human impacts on the environment (MEA, 2005), this research approach presented an alternative to top-down environmental regulation. That is, ES were originally intended to facilitate collaborative management and provide a shared framework for assessing the values of ecosystems while incorporating those values into market decisions (Costanza et al., 1997; Daily, 1997).

The ES framework offers a common language for communicating across research disciplines, among environmental managers, and through global markets. However, critics have argued that the ES framework as a communication tool has become overshadowed by economic thinking (Bateman et al., 2013), making it more susceptible to the commodification of goods and services bought, sold, and traded for environmental protection (Gómez-Baggethun et al., 2010; Kosoy and Corbera, 2010). The operationalization of the ES concept is as much a political process as an economic one, which is complicated by the fact that academics, policy-makers, and the public may not clearly understand the relationship between markets and institutions (Norgaard, 2010). Although it behooves researchers to develop shared and pluralistic understandings the

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Abbreviations: ES, ecosystem services; EPA, Environmental Protection Agency; FRMES, Federal Resource Management and Ecosystem Services; FEGS, Final Ecosystem Goods and Services; IPBES, Intergovernmental Platform on Biodiversity and Ecosystem Services; NAICS, North American Industrial Classification System.

[*] Corresponding author at: NESB A245, Natural Resource Ecology Lab, Campus Delivery 1499, Colorado State University, Fort Collins, CO 80523-1499, USA.

E-mail addresses: Cara.Steger@ColoState.edu (C. Steger), cevers@pdx.edu (C. Evers), benjamin.branoff@upr.edu (B. Branoff), maxnp@pdx.edu (M. Nielsen-Pincus), cwardrop@purdue.edu (C. Wardropper), cvanripe@illinois.edu (C.J. van Riper).

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ES framework (van Riper et al., 2017), some degree of standardized methods for measurement and valuation are needed in order to move from theory to practice. Standardization facilitates implementation, yet efforts to standardize both the concept and practice of the ES may diminish its ability to function as a communication device for bridging social worlds and disciplinary perspectives.

A growing number of studies have framed ES as "boundary objects" owing to tensions surrounding their interpretive flexibility (e.g., Abson et al., 2014; Kenter, 2016; Kull et al., 2015; Schröter et al., 2014). We believe this body of work is informative but incomplete, because it fails to engage with the dynamic nature, scale, and scope of the boundary object concept. Consequently, we provide a comprehensive definition and offer examples that describe the boundary object concept and "life cycle." Specifically, we argue that parts of the ES concept are transitioning out of boundary object status due to ongoing standardization and classification based on agreed-upon rules and definitions aimed at reducing inconsistencies and potentially conflicting practices. We then consider how the characteristics of ecosystem service types (i.e., provisioning, regulating and cultural) enable certain services to continue to operate flexibly. Provisioning, regulating and cultural services warrant particular attention due to their tangible and intangible qualities, as well as their importance in the economic valuation process, which may facilitate standardization. We conclude by exploring the implications of discussing ES in terms of boundary objects for transdisciplinary collaboration.

2. Boundary Objects

2.1. Characteristics of Boundary Objects

Boundary objects were introduced in the field of science and technology studies to theorize how heterogeneous actors cooperate and share coexisting opinions within scientific work and society (Star and Griesemer, 1989). Boundary objects were identified as objects or ideas that emerged through collaboration and dialogue which were both adaptable to local needs yet "robust enough to maintain a common identity" (Star and Griesemer, 1989, p. 393). These objects were posited as analytical concepts used to describe interaction and translation so that groups could work together when consensus was neither possible nor desired (Star, 2010). Boundary objects are both abstract (e.g., ideas, classification systems, or concepts) and concrete (e.g., images, maps, or tools). For example, Star and Griesemer (1989) described the boundary objects produced in natural history work as simultaneously encompassing specimens, field notes, and maps while also representing "nature" as it was conceived by the diverse sponsors, theorists, and amateurs involved in their production.

Three distinguishing features of boundary objects enable them to function across multiple actors (Bowker and Star, 1999; Star, 2010; Star and Griesemer, 1989). First, a boundary object has "interpretive flexibility," meaning that it is able to satisfy the needs of users from different social worlds while facilitating communication between them (Star and Griesemer, 1989). Social worlds can be spaces where individuals communicate through shared discourse (Strauss, 1978) or broader "communities of practice" that interact in a shared cultural space (Wenger, 1998). This characteristic has been the most studied aspect of boundary objects to date (Star, 2010); however, taken alone, interpretive flexibility could be applied to a vast array of ideas or objects and may seem counterintuitive for facilitating communication. Therefore, a boundary object must secondarily address an information need arising from work processes, such as a need to classify or organize data. The boundary objects that arise from these needs in turn influence the form and structure of dialogue (Table 1; Star, 2010). Third, a boundary object is not a static concept but instead requires movement between a general, ill-structured form and local, tailored applications of a given idea (Star, 2010). Thus, the ability of a boundary object to tack back-and-forth between social worlds—to simultaneously exist in a specific state for one discipline while being universally vague across all disciplines—makes them particularly powerful transdisciplinary tools to be invoked in policy and decision-making (Star, 2010).

2.2. Types of Boundary Objects in Environmental Research

Star and Griesemer (1989) identified four distinguishable categories of boundary objects (Table 1). The first kind of boundary object is one that acts as a "repository," defined as an object for organizing and indexing information within society or scholarship. Star and Griesemer (1989) used the establishment of the Museum of Vertebrate Zoology at the University of California at Berkeley as an example to show that repositories standardize the delivery of information without restricting the ways in which users interpret and apply the knowledge provided. Similarly, boundary objects can be used to facilitate collaboration through another category termed "ideal types." By remaining vague, ideal types can be used locally while facilitating communication across a broader scale (Star and Griesemer, 1989). The biological concept of a species is an ideal type, because it enables scientists to make legible the diversity of organisms and processes. Scholars and practitioners have treated the ES concept as an ideal type to identify the diversity of benefits people obtain from the environment, which has proliferated a variety of frameworks for organizing and classifying these benefits (e.g., Díaz et al., 2015; Muhar et al., 2017; Ostrom, 2009). For example, the MEA (2005) defined ES as 'benefits obtained from ecosystems,' which allows for a broad range of interpretations across disciplines and stakeholder perspectives despite the various forms of material and non-material benefits of nature.

Boundary objects can also represent "coincident boundaries" that share the same material structure but have different content and/or interpretations depending on the perspectives of the user (Star and Griesemer, 1989). Clark et al. (2011) applied the boundary object concept to navigate what constituted useful knowledge across different communities involved in community forestry around the world. These authors highlighted the need for developing tangible boundary objects that were tailored to a specific context. Several of the products most valued by both communities and scientists were drawings, maps, and physical models of the landscape; these objects have coincident boundaries and represent the same geographic space but allow for multiple interpretations and uses by practitioners. In contrast to the coincident boundaries category, "standardized forms" are boundary objects that standardize content and streamline communication across diverse groups (Star and Griesemer, 1989). A standardized form allows information to travel without losing meaning if it maintains a specific structure across groups, while not being limited by the ways information is interpreted and applied. For example, ecological indicators may be considered standardized forms that assess ecological quality and allow for comparisons across diverse areas. However, if ecological indicators become too inflexible, they incite conflict and impede effective communication (Turnhout, 2009).

2.3. Boundary Objects as a Dynamic Process

As an analytical tool, the boundary object concept is useful for providing insight into the dynamic process of collaboration, including how it produces these objects, generates material effects, and potentially transitions into standardized "infrastructure" (Star, 2010). Infrastructures are the tools, work practices, terms, and technologies that become embedded in and support a community of practice (Star and Ruhleder, 1996; Bowker and Star, 1999). Whether or not something functions as a boundary object depends on the criteria and forms described in Sections 2.1–2.2, as well as the scale and scope of its use over time (Star, 2010). Some objects or concepts may be more useful than others and may depend on the number and diversity of actor groups engaged with its production and maintenance (Star, 2010). Boundary objects, like infrastructure, are therefore both "product and process" (Star and Ruhleder, 1996, p. 111) with conceptual and material effects that

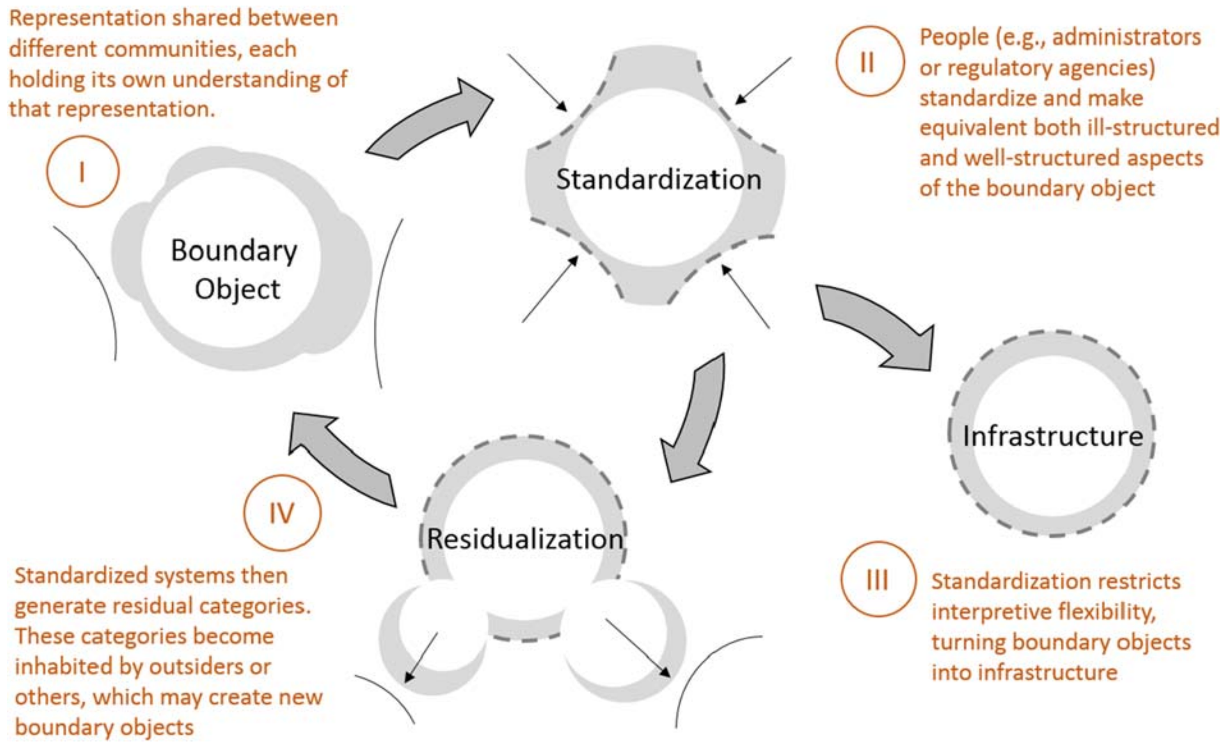
Table 1
Definitions and examples for four types of boundary objects. NAICS is the North American Industrial Classification System, while FEGS stands for Final Ecosystem Goods and Services.

Type	Description	General example	Ecosystem services example
Repositories	Indices that order and group objects; users can reference this index without negotiating purpose with other users	Libraries or museums; federal register; encyclopedias	Environmental Protection Agency's FEGS programs account for benefits of ecosystem services and draw on the NAICS classification schema (Landers and Nahlik, 2013)
Coincident boundaries	Commonly recognized boundaries allow different and overlapping content; users conduct work autonomously while cooperating with a common reference	Maps or political boundaries; jurisdictional agreements; cadastral tax maps	Geographic Information Systems store sets of attributes related to ecosystem services within a common polygon
Ideal type	A model, term or concept that fails to adequately describe any one particular thing; its abstraction allows for communication and cooperation	Biological concept of a species; atlases	The MEA (2005) leveraged hundreds of scientists to propose four classes of ecosystem services, each with numerous sub-categories
Standardized forms	A device for organizing information that facilitates communication; requires simplification to ensure objects are legible despite limited information about their origin or context.	Data collection form; US census data; tax forms; legal requirements	Spatial data (e.g., land cover, soils, vegetation, climate) are described in terms of ecosystem service production functions, translating a standardized set of information into a consistent output

coproduce one another in an iterative and relational cycle (Jasanoff, 2004). Something becomes a tool, or infrastructure, in practice when it is used in a particular way (Star and Ruhleder, 1996), while at other times remaining an idea or concept. Thus, “ecosystem services” operate as either tools (i.e., infrastructure) or concepts (i.e., boundary objects) depending on the context of their use.

Boundary objects are ephemeral, changing entities that follow a dynamic process or “life cycle” over time (Fig. 1). Initially, the inherent vagueness and flexibility of a boundary object can complicate how it is operationalized. This causes users such as administrators or regulatory agencies to work towards institutional standardization—an agreed-upon set of rules or definitions—so that information can be transferred effectively and accurately across scales and social worlds. Standardization seeks to reduce uncertainty and facilitate collaboration across distances and heterogeneous metrics or measurements, and can be difficult to change once put in place (Bowker and Star, 1999). There is, of course, no guarantee that the “best” standard will emerge from collaboration, because standards are established for a variety of socio-political reasons (Castree, 1995; Harvey, 2004; Prudham, 2009) and institutional management regimes (Scott, 1998), resulting in immutable mobiles (Latour, 1987) steeped in power dynamics that influence the production of knowledge (Brand and Jax, 2007). Thus, there is a strong need for ES to be operationalized in equitable and transparent ways that remain sensitive to the causes and consequences of standardization.

Given that a fundamental quality of a boundary object is its ability to tack back-and-forth between ambiguous and specific meanings, standardization may restrict flexibility and transform a boundary object into infrastructure. A key feature of infrastructure is that it can evolve and become transparent or fixed across broad reaching scales and scopes of use (Star and Ruhleder, 1996; Star and Bowker, 2002). This is an imposition of standards, in that classification systems lead to the creation of infrastructure that is so embedded in common use that it becomes invisible and assumed (Star and Ruhleder, 1996). Examples of common infrastructure are information technology (Pipek and Wulf, 2009) or data management systems (Karasti and Baker, 2004), which most users never explicitly think about during use. Infrastructures can also be taken-for-granted or become norms that embody standards and classifications (Star and Bowker, 2002). The process of creating infrastructure



Representation shared between different communities, each holding its own understanding of that representation.

People (e.g., administrators or regulatory agencies) standardize and make equivalent both ill-structured and well-structured aspects of the boundary object

Standardization restricts interpretive flexibility, turning boundary objects into infrastructure

Standardized systems then generate residual categories. These categories become inhabited by outsiders or others, which may create new boundary objects

Fig. 1. Boundary objects are dynamic concepts that maintain permeable boundaries for interpretation and communication (Phase I). In response to standardization (Phase II), boundary objects can move into a state of infrastructure (Phase III) or experience residualization (Phase IV) that can in turn form new boundary objects. Adapted from Star (2010).

involves a boundary object phase where alternative possibilities are considered and rejected in favor of the final product. In this sense, a boundary object that “was once an object of development and design” can become “sunk into infrastructure over time” (Star and Bowker, 2002, p. 233).

Infrastructure can naturalize political conflict or difference because it regulates and formalizes communication to ignore a messy reality (Bowker and Star, 1999). Infrastructure can also be paradoxical in that it simultaneously creates a commonly shared foundation for members of distinct social worlds while also hampering creative applications of those same concepts in the future (Star and Ruhleder, 1996). Infrastructure can be difficult to reverse once it is constructed, because fixed interpretations become layered and embedded by other disciplines and sectors (Bowker, 2000). However, given that boundary objects are iterative and relational, one group's boundary object may be another group's barrier (Star and Ruhleder, 1996) if members of that group are outside the relevant collaboration, or share a different cultural context. Additionally, as standardization produces infrastructure, residuals emerge that do not fit neatly into predetermined categories. These residual objects may in turn become boundary objects in their own right, thus continuing the boundary object life cycle.

Whether an object continues to function as a boundary object depends on its evolution through flexible, organic collaborations and continued use across different social worlds. In this regard, boundary objects can be actively maintained if users accept there will be flexible definitions and methodologies in other spheres of use. Similarly, objects may transition out of boundary status if users agree that higher precision and commonality are needed for operationalization and making manageable inferences about standardized relationships. The ES framework is often hailed as being capable of facilitating cross-scale collaboration, yet there is limited evidence (Abson et al., 2014) and high uncertainty about whether transdisciplinary collaboration can proceed without consensus on definitions and methods. Transdisciplinary collaborations bring diverse academic participants (i.e., interdisciplinarity) and practitioners (i.e., government, private sector, citizen groups, etc.) together in a problem-oriented research process that seeks solutions to scientific and societal issues (Lang et al., 2012). As the ES concept moves towards more rigid structures, shared language, and common frameworks mandated by authorities, it risks losing its dynamic ability to move freely among different contexts and applications. We suggest the standardization of ES reflects the life cycle of a boundary object, and is a pattern that is seen across both academia and practice.

3. The Standardization of Ecosystem Services

3.1. Standardization in Academia

Early ecosystem service research relied heavily on economic assumptions about knowledge and its acquisition (Bockstael et al., 2000; Costanza et al., 1997), leading to research outcomes that were pursued through a relatively narrow epistemological frame (McCauley, 2006; Turnhout et al., 2014). We propose that standardized definitions and valuation methodologies was at first a boon to ES as boundary objects, allowing the concept to take a form that could be transferred across social groups while still leaving enough flexibility to operate differently within distinct spheres. However, ES have come to occupy a highly contested space in academia due to disagreement about the ethics of monetizing nature, strategies for valuation, and the definition and classification of ES (Dempsey, 2015; Gómez-Baggethun et al., 2010; Schröter et al., 2014). In particular, contentious debates have surrounded the degree to which the environment can and should be commodified in response to the ephemeral and oftentimes perverting relationships between markets and nature (Fairhead et al., 2012; McCauley, 2006). Other influential debates have focused on the impacts of the ecosystem service concept on biodiversity conservation and social justice (Gómez-Baggethun and Ruiz-Pérez, 2011; Schröter et al., 2017).

Fundamental disagreement on the definition and classification of ES has spurred new ideas and classification systems (Muhar et al., 2017; Nahlik et al., 2012; Wallace, 2007). Abson et al. (2014) argued that the language used by scholars of ES differed significantly based on the disciplinary background or thematic niche of the scholar, and used this finding to indicate the absence of boundary object status for ES. We argue that these diverse definitions, vocabularies, and classification systems have instead maintained the ES framework as a boundary object by preventing it from being too structured within a single discipline. As evidence, we point to the existence of cross-disciplinary collaborations around the ecosystem service concept (e.g., the Intergovernmental Platform on Biodiversity and Ecosystem Services, IPBES) indicating that the concept is still operating flexibly across disciplinary boundaries, while becoming increasingly structured within individual disciplines. This movement between a general, ill-structured form and local, tailored applications is a critical aspect of the boundary object concept (Star, 2010) that is currently playing out in the study of ES. For example, some scholars have emphasized the difference between process and product in the different types of ES, grouping regulating and supporting services as processes (“services”), while provisioning and cultural services are grouped as products (“benefits”) (Potschin and Haines-Young, 2011; Wallace, 2007). Other scholars have focused on the distinctions between cultural services from the other material processes or products of an ecosystem (Chan et al., 2016; Chan et al., 2012; Daniel et al., 2012; Fisher and Turner, 2008; van Riper et al., 2017). Despite these different lenses, research has continued to focus on assigning economic value to ES to make the concept *useful* for decision-makers and practitioners (Daily et al., 2009). These different objectives in classification reveal diverse positions on the materiality of ES and reinforce their ability to serve as boundary objects.

The existence of multiple definitions and frameworks is not sufficient to meet the criteria of a boundary object; there must also be some degree of collaboration, and it is not clear whether interdisciplinary ecosystem service research will continue without requiring some degree of standardized consensus. Indeed, some scholars urge consensus on a definition and classification system for measuring ES to reduce the inconsistency and incompatibility of current ES assessments at various scales and contexts (Nahlik et al., 2012), though that is easier said than done. Previous definitions and frameworks have been criticized as being overly reductionist with regard to the relationship between people and nature (Fish, 2011; Fisher and Brown, 2014), thus fostering a narrow interpretation of the concept that is biased towards disciplinary perspectives from ecology and economics (van Riper et al., 2017). These critiques have led some scholars to call for a broader framing of the definition of ES with greater consideration of the complexities that are overlooked in simplistic models of service provisioning (Norgaard, 2010). These debates underscore trade-offs between the verifiability that comes with conceptual clarity versus the creative thinking and problem-solving facilitated by conceptual vagueness (Strunz, 2012), which is key to the boundary object concept. For example, Nahlik et al. (2012) suggested that increased structure and specificity, rather than broader frames and language, will better facilitate transdisciplinary collaboration through integrating language and methods from natural science, social science, and public sectors. Most recently, the IPBES has attempted to find the middle ground between these schools of thought in its conceptual framework, which organizes ES using broad and inclusive categories (e.g., ‘nature’, ‘good quality of life’, ‘nature's benefits to people’) together with explicit language of multiple disciplines (Díaz et al., 2015). It is still unclear whether the IPBES conceptual framework will successfully resolve these competing frameworks, definitions, and classifications to advance ES towards infrastructure by producing consensus across disciplines and epistemological divides.

As illustrated by our conceptual model, this call for standardization should be approached cautiously and with full understanding that some ES may become institutionalized as infrastructure in academia. The push towards greater conceptual and methodological clarity in the study of ES is a call for consensus, yet a critical hallmark of boundary objects is that they can facilitate collaboration without requiring consensus. Effective interdisciplinary teams promote mutual understanding of one another's epistemological worldviews, emphasizing the importance of developing and communicating diverse ideas to address complex problems (Bosque-Pérez et al., 2016; Eigenbrode et al., 2007). Thus, a shift towards greater consensus may result in more efficient tools for ecosystem service valuation and measurement, but it may also limit the ability of the ES concept to serve as an interdisciplinary bridge for deliberation.

3.2. Standardization in the U.S. Federal Government

The concept of ES has fueled a silent revolution surrounding environmental governance and federal activity in the U.S. that has spanned nearly two decades. Many federal agencies have worked towards consensus on the definition and use of ES. For example, between 1998 and 2011, the executive branch convened several working groups aimed at accelerating adoption of ES across agencies through guidelines and standardized databases (Schaefer et al., 2015). These early initiatives centered on economic concerns and led to the creation of the U.S. Department of Agriculture's Office of Environmental Markets. In May 2012, the National Ecosystem Services Partnership convened federal decision-makers to identify challenges limiting their ability to integrate ES concepts into management and planning, which resulted in the Federal Resource Management and Ecosystem Services (FRMES) guidebook (nespguidebook.com). Because these agencies responded directly to regulations and directives, paralleled efforts to standardize the ES framework were united under the common goals of improved cost-effectiveness, innovation, resilience, and public engagement in natural resource decision making (FRMES, 2017). As agencies engaged more deeply with the ES concept, stronger social and ecological themes emerged and the disciplinary perspectives incorporated into management plans multiplied (Scarlett and Boyd, 2015).

Despite top-down efforts to rapidly standardize ES by the federal government, the concept has continued to function as a boundary object by simultaneously allowing local specificity and broad vagueness. In 2013, researchers from the Environmental Protection Agency (EPA) identified more than 207 programs across nine federal agencies focused on ES (Cox et al., 2013), indicating that individual agencies were using the concept in diverse ways. The EPA also highlighted collaborative endeavors across agencies when publishing the first version of its classification system for Final Ecosystem Goods and Services (FEGS) (Landers and Nahlik, 2013), which was designed to be compatible with the North American Industrial Classification System used to classify business establishments for the purpose of better describing the U.S. economy. Although this approach facilitated dialogue and potential collaboration between agencies, FEGS was not embraced as a guiding framework. The National Oceanic and Atmospheric Administration, part of the Department of Commerce, has relied on ecosystem-based management of human activity and indicated non-market valuation methods are desirable pathways for integrating ES into decision-making contexts (FRMES, 2017). This approach differs from the U.S. Forest Service in the Department of Agriculture, where researchers and practitioners have relied more heavily on a broad definition that complements more traditional economic definitions and approaches to operationalizing the concept (USDA, 2017).

In 2015, the standardization of ES entered a new era when President Obama's administration issued a joint-memorandum that directed federal agencies to account for ES in their decision making (Donovan et al., 2015). The memorandum set in motion a review of current assessment and valuation practices used by federal agencies to standardize the process of environmental accounting via a set of recommended best practices. This broad call across agencies aimed to normalize the processes, language, metrics, and objects utilized in decisions (Polefka and Sutton-Grier, 2016) and ensure managers would be better equipped to account for social-ecological change. The 2015 joint-memorandum, and future pushes towards more systematic and regulated processes represents a turning point in the life cycle of ES as a boundary object in the U.S. federal government. In response to this movement, overly rigid standardization could hinder the transdisciplinary application of ES in projects that require broad stakeholder collaboration.

4. Transition to Infrastructure and Creation of Residual Categories

We contend the utility of the ES framework can be enhanced by considering the different types and dimensions of boundary objects (e.g., ideal types, standardized forms), in addition to recognizing the tension between flexibility and standards in an iterative life cycle. Earlier, we discussed how ES were operationalized within academic and practitioner worlds to illustrate how: (a) the boundary 'nature' of ES takes multiple forms, and (b) the concept has evolved in a way that can be traced along the boundary object life cycle. In this section, we use three categories of ES - regulating, provisioning and cultural services - to show how standardization can create infrastructure while simultaneously forming new, residual categories. Given recent trends in academia and the U.S. federal government for agencies to account for ES in decision-making, we anticipate that regulating and provisioning services are likely to transition into infrastructure while cultural services may be cycling into a residual category.

4.1. Regulating and Provisioning Services Transforming Into Infrastructure

Regulating and provisioning services are more easily measured and quantified than supporting and cultural services due to their more material and observable nature, which we assert facilitates standardization more readily. Regulating services are the benefits obtained from natural processes, such as climate regulation and water purification. Some scholars consider them "intermediate services" that produce "final goods" in the form of provisioning services (Fisher et al., 2009). Provisioning services include resources that are necessary for human survival such as food, water, fuel, and medicine. They are tangible products of ecosystems able to be extracted and owned, and are thus easily standardized, commodified, and traded. Standardization of natural resources represents long historical processes; to take an old example, grain was one of the first commodity goods produced, yet its standardization continues into the modern era as grain grown around the world is transformed from a locally harvested crop into to a graded commodity (Cronon, 2009). Other standards are still emerging, in that recent concern over greenhouse gas emissions has led to the creation of carbon markets where offset credits are produced from the ecological process of carbon sequestration in forests (Norgaard, 2010). The United Nations Framework Convention on Climate Change has championed programs geared towards reducing emissions from deforestation and degradation (REDD) in forest-rich developing countries, allowing them to receive payments from other carbon emitting countries in exchange for the carbon sequestration and biodiversity value of maintained forest cover (Gibbs et al., 2007).

Standardized indicators can provide benefits for land management agencies by allowing tradeoffs and synergies to be analyzed and compared across systems. Numerous methodologies exist for valuing provisioning and regulating services, including both market and non-market approaches. Decision-makers tend to adopt market approaches to quantifying the benefits of the environment for pragmatic reasons (Fisher and Brown, 2014) related to the relative ease of quantifying and translating provisioning and regulating services into simple and clear decision support tools (Rol, 2008). For example, the U.S. Forest Service partnered with Denver Water to estimate the damages to water quality that could be avoided by restoring forests after wildfire. The federal agency and public utility engaged in the standardization of provisioning and regulating services by agreeing to a set of methods for measuring the economic benefits of filtering and producing fresh water through natural processes, rather than supporting investment in water treatment and wastewater facilities. In the end, the USFS contributed $32 million towards restoration that was rationalized in economic terms for the public good (Deal et al., 2014). The Denver watershed example was a landscape scale management decision made possible through collaboration and standardization among federal, state, and local agents, which was facilitated by the valuation of ES.

Previous researchers have developed comprehensive models of environmental processes to describe tradeoffs in direct and empirical terms. Using production functions, models like InVEST (www.naturalcapitalproject.org) have translated changes in land cover and land use into measurable benefits so that provisioning and other services can be compared and modeled to guide future decisions. Similarly, programs such as the U.S. Geological Survey mapping application Social Values for Ecosystem Services (https://solves.cr.usgs.gov/) were developed to standardize and quantify cultural services to facilitate comparison to landscape metrics (Sherrouse et al., 2011). While the ES concept may have operated as a boundary object during the early stages of these collaborations, the final models are expressed digitally through computer code that requires unambiguous definitions in a specific programming language, indicating that the implementation of ES in this transdisciplinary context has moved the concept into a standardized phase.

Although useful, the standardization and widespread adoption of economic methods for valuing provisioning services has drawbacks, including the potential for scarcity due to speculation-induced changes in commodity pricing (Lagi et al., 2015). There is also a risk of overshadowing non-monetary values (Rodríguez et al., 2006), in that provisioning services placed in an economic framework may diminish consideration of important intrinsic values that are more difficult to quantify or neglect feelings of moral obligations and other social psychological processes that shape how people value processes and services (Bowles, 2008; van Riper et al., 2017). Indeed, a deterministic perspective that the benefits of nature are based strictly on utility may not fully capture the reasons why stakeholders engage with and feel connected to places (Winthrop, 2014).

While it may be relatively easy to price provisioning services, there are potential disadvantages for resource management agencies placing too much weight on one particular service. Payments for ES schemes, for example, may create perverse incentives such as encouraging the clearing of new land for agricultural subsidies (Wu, 2000). In these contexts, ascribing ownership to commodities does in fact require winners and losers. For example, indigenous communities may lack documentation to assert their land ownership (Redford and Adams, 2009). Scholars and practitioners should consider actively maintaining provisioning services as boundary objects in certain contexts so that their definition and use does not become overly focused on economic valuation, and thus susceptible to the disadvantages summarized here. Alternatively, there is potential for compromise in the standardization of provisioning services for specific use contexts, such as land use planning and life cycle analysis, while still maintaining the concept as a boundary object at broader organizational scales (Polasky et al., 2015). The locally tailored and globally vague use of the term would allow a provisioning service to function as a boundary object as it tacks back and forth between scales (Star and Ruhleder, 1996). Maintaining this flexibility in the ES concept would therefore strengthen the potential for communication across disciplines and communities.

4.2. Cultural Services as Residual Categories

Cultural services are the non-material benefits people obtain from ecosystems, such as inspiration, cultural identity, and recreation. These services arise from intimate relationships between people and their environments, and as such are difficult to approximate through socio-economic substitutions. Cultural services include nonmaterial qualities that are difficult to quantify, are often implicitly represented in decision-making, and tend to be excluded from cost-benefit analyses (Chan et al., 2012). In fact, the nature of cultural services renders them ill-suited to the notion of a "service" that implies all environmental products are consumed by society (Satterfield et al., 2013). Although some cultural services such as outdoor recreation and tourism settings are more likely to be treated like interchangeable commodities (Williams et al., 1992), other cultural services represent deeply held values, place-based considerations of culture and spirituality, and contested landscapes that inherently remain outside of a market framework (Milcu et al., 2013; Plieninger et al., 2015). Indeed, given the tangibility of provisioning space for recreation and tourism, and the clear market connections, these services might be more accurately characterized as provisioning services.

Many cultural services have resisted standardization because they do not fit neatly into the ES framework. They are the least well-understood of the service types and practitioners have struggled to incorporate them into current decision-making frameworks (Schaefer et al., 2015; Winthrop, 2014). Scholars and practitioners alike wrestle with the definition and measurement of cultural services, and have often given preferential treatment to the ongoing standardization of other ecosystem service types (with the exception of recreational services). For example, the EPA's EnviroAtlas (https://www.epa.gov/enviroatlas) separated ES into eight categories; three categories address different types of provisioning services, while all cultural services are grouped into a single category. Provisioning services are more clearly defined and understood, even in relation to other provisioning services. Similarly, a recent water diversion project in California was mandated to consider cultural services in the design of the project but decision-making from the science commission board focused on utilitarian rather than cultural values (Norgaard, 2017). In this context, cultural services resembled a residual category that remained marginalized while other types of ES were the focus of standardization.

There are advantages and disadvantages to conceptualizing cultural ES as a residual of the boundary objects life cycle. On one hand, cultural services' resistance towards standardization reveals the contextual nature of valuation and the ability of stakeholders to imbue cultural services with different meanings (Chan et al., 2016). Identifying and monitoring these residual services will require greater collaboration among stakeholder groups and active facilitation by decision-makers to maintain interpretive flexibility. However, differential treatment of the ecosystem service categories may limit engagement with disciplines for whom this framework is integral, as well as stagnate attempts to incorporate all ES into national level planning frameworks (Scholte et al., 2015). Moreover, as articulated by Kenter (2016), "Splitting off non-monetary/sociocultural/cultural service values is in danger of not just leading to separate *value domains* but also to separate *knowledge domains*" (pp. 367). That is, if cultural services receive different treatment than other service types, the diverse epistemologies and ontologies required for capturing the full range of cultural services may be disregarded in the way society articulates the multiple values of nature. It is crucial that future research and practice remain cognizant of the potential implications of standardization for the valuation of all types of ES.

5. Conclusion: Ecosystem Services as Boundary Objects in Transdisciplinary Work

Several authors have recently proposed that ES operates or could potentially operate as a boundary object (Abson et al., 2014; Kenter, 2016; Kull et al., 2015; Schröter et al., 2014). Although this body of work has affirmed the importance of interpretive flexibility in ecosystem service valuation, we contend that if ES are to function as a boundary object, implementation must arise from an organizational or communication need in society, and collaborators must ensure that their conceptualization remains simultaneously vague in general use while being specific in local use, as articulated by Star (2010). Future transdisciplinary work around ES should build on the foundation established in previous research, while bringing greater nuance to the process of collaboration through improved understanding of the different forms and dimensions of boundary objects (e.g., ideal types, standardized forms). The varied levels of tangibility associated with different ES influences the way this concept moves through the boundary object life cycle - a process that will work differently for provisioning, regulating, supporting, and cultural services. Moreover, material and non-material services co-produce each other over time, which underlines the importance of recognizing when tools and/or concepts move in and out of boundary object status. Identifying when something does or does not function as a boundary object is critically important not for "policing" the term, but for the analytical implications this label brings.

Maintaining the ES framework as a boundary object has implications for the translation of values and potential for facilitating transdisciplinary work across academic disciplines and work sectors. Lang et al. (2012) explicitly called for transdisciplinary projects to collaboratively define objects early in the research process to ensure that various objectives and disciplinary perspectives are given equal weight. This is particularly important for transdisciplinary, action-oriented research (Lewin, 1946), whereby the end goals for researchers (e.g., advancing theory vs monitoring a species) may differ from the end goals of stakeholders (e.g., addressing a social injustice) involved in a collaboration. A flexible conceptual definition and diversity of ecosystem service tools can facilitate dialogue about these (dis)similar goals in transdisciplinary work, which has been shown to promote effective problem solving across disciplinary divides (Eigenbrode et al., 2007).

The science-policy interface relies on social and natural science research to develop indicators that will sustain society and the environment, while leaving space for deliberation and negotiation of values. The ES framework as a boundary object carries great potential for facilitating communication among diverse social worlds (Turnhout, 2009), especially if flexibility is maintained early in the conceptual phase of a project (Saarela and Rinne, 2016). However, there is an inevitable risk that a concept or tool will lose its value over the course of a project because researchers or practitioners have different levels of familiarity with its meaning or purpose. In this sense, standardization may be instrumental in applying the ES framework in particular contexts. It is critically important to keep these tradeoffs in mind and recognize the differential effects of standardization on the various types of ES, particularly for U.S. federal agencies or other groups that are mandated to account for multiple values of nature across broad geographic scales. We urge practitioners of the ES concept to rely on the most relevant disciplinary knowledge (Abel and Stepp, 2003), rather than allowing standardized solutions to determine the boundary of a given problem.

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