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Towards a Comprehensive Approach to Quantifying and Mapping Ecosystem Services Flows

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Towards a comprehensive approach to quantifying and mapping ecosystem services flows

Ferdinando Villa[1], Kenneth J. Bagstad[2], Gary W. Johnson[3], Brian Voigt[3]

Recent ecosystem services research has highlighted the importance of spatial connectivity between ecosystems and their beneficiaries. Despite this need, a systematic approach to ecosystem service flow quantification has not yet emerged. In this article, we present such an approach, which we formalize as a class of agent-based models termed "Service Path Attribution Networks" (SPANs). These models, developed as part of the Artificial Intelligence for Ecosystem Services (ARIES) project, expand on ecosystem services classification terminology introduced by other authors. Conceptual elements needed to support flow modeling include a service's rivalness, its flow routing type (e.g., through hydrologic or transportation networks, lines of sight, or other approaches), and whether the service is supplied by an ecosystem's provision of a beneficial flow to people or by absorption of a detrimental flow before it reaches people. We describe our implementation of the SPAN framework for five ecosystem services and discuss how to generalize the approach to additional services. SPAN model outputs include maps of ecosystem service provision, use, depletion, and flows under theoretical, possible, actual, inaccessible, and blocked conditions. We highlight how these different ecosystem service flow maps could be used to support various types of decision making for conservation and resource management planning.

Keywords: Ecosystem services, spatial flows, beneficiaries, Service Path Attribution Network (SPAN), Artificial Intelligence for Ecosystem Services (ARIES)

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1. Introduction

Since the earliest formalizations of the ecosystem services concept, scientists have constructed lists of ecosystem services. The Millennium Ecosystem Assessment (2005) has achieved perhaps the greatest scientific consensus in recent years. Yet, soon after its publication a stronger focus on the beneficiaries of ecosystem services was advocated as a prerequisite to dealing with “double counting” of ecosystem service values (Boyd and Banzhaf 2007, Wallace 2007). A beneficiaries-based approach has also been advocated to provide linkages to green accounting systems that incorporate the value of ecosystem services into mainstream macroeconomic measures like GDP (Boyd and Banzhaf 2007, Haines-Young and Potschin 2010, Nahlik et al. in press). Others have described the difficulties presented by the “spatial mismatch” between the ecosystems that provide value and people that enjoy services (Ruhl et al. 2007, Costanza 2008, Fisher et al. 2009). While important challenges remain in the ecological and economic understanding of ecosystem services, an even more basic set of geographic questions – “where are ecosystems supplying benefits” and “who and where are people using ecosystem services” – too often remains unanswered in ecosystem services studies.

Early efforts to map ecosystem services via modeling (Eade and Moran 1996, Chan et al. 2006) or spatially explicit value transfer (Troy and Wilson 2006) paid little attention to ecosystem service flows. Ruhl et al. (2007) and Fisher et al. (2009) described some patterns of transmission of a service from provision to benefit areas, reflecting the understanding that ecosystems and their beneficiaries are often not co-located. However, these contributions fall short of providing systematic quantitative tools to measure and map ecosystem service flows. To date no systematic solution to this problem has been proposed.

The inability to consistently describe, quantify, and map ecosystem service flows hampers the application of ecosystem services concepts to policy making. Ecological production functions (Daily et al. 2009), increasingly used to quantify an ecosystem’s ability to supply social benefits, do not reflect the locations of beneficiaries or the spatial and temporal flow of services; as such, they only quantify in situ or theoretical service provision. Without quantifying actual flows and use of services, the values of most services are not easily understood. While some ecosystem service models are beginning to address this problem by quantifying service flows (especially for hydrologic services and pollination, Kareiva et al. 2011), a systematic treatment of ecosystem service flows that can lead to generalizable results and guidelines for decision making has not yet been developed.

Regrettably, even the term “ecosystem service flow” is ambiguous. In this contribution, we use it to refer to the transmission of valuable service from ecosystems to people. Another common usage of the term refers to the annual flow of benefits accruing to people as generated by stocks of ecosystem structure (Daly and Farley 2004).

We present a framework for modeling ecosystem services that consistently and fully accounts for the “spatial mismatch” between ecosystem services and their beneficiaries. We developed this approach as part of the Artificial Intelligence for Ecosystem Services (ARIES) modeling platform (Villa et al. 2009, Villa et al. 2011, ARIES 2012). However, the flow modeling formalization presented here can apply generally to the quantification of ecosystem service flows.

We first describe the terminology needed to communicate the spatial dynamics of ecosystem services (Section 2). We then provide examples of application for five of the nine classes of ecosystem services currently modeled as part of the ARIES project. We conclude by discussing advantages, conceptual obstacles, and remaining research needed to use ecosystem service flow information to support decision making.

2. Concepts to operationalize ecosystem service flows

In order to address ecosystem service flows in a consistent manner, we adopt an approach that includes five key elements (Table 1). The first is the identification of ecosystem service beneficiaries who benefit from “ecological endpoints” (Boyd and Banzhaf 2007) or “final ecosystem goods and services” (Johnston and Russell 2011). The second is the identification, for each benefit type, of a carrier, expressed in physical units or relative rankings, that transmits the service by connecting ecosystems and people. The third is establishing whether use of or contact with the carrier is beneficial or detrimental to human well-being. As a fourth step, the use of the carrier is classified as rival or non-rival, and its sources, sinks, or use as biophysically limited or unlimited. Lastly, we identify the flow type used in routing the carrier from ecosystems to people – or for some services routing people to ecosystems. The SPAN (Service Path Attribution Network: Johnson et al, 2010, 2012) simulation algorithms proceed by using data and models that quantify and map source locations (ecosystems that generate an ecosystem service carrier), sink locations (landscape features that can absorb, degrade, or deplete a carrier), and use locations (human beneficiaries of the service), connecting these areas to quantify service flows.

Table 1. Summarized concepts to support ecosystem service flow quantification

Concept	**Definition**	**Purpose for flow modeling**
Benefits-based approach to ecosystem services modeling	Concrete, unique, and final beneficiaries of ecosystem services	Avoids double counting, supports spatially explicit mapping and valuation of beneficiaries
Ecosystem service carrier	A mobile matter, energy, or information quantity represented in physical units or relative rankings	Used in SPAN to track the route and quantity of the service flow between source, sink, use locations
Provisioning service	Services where interaction with the carrier is beneficial to users	Defines sources as valuable and sinks as detrimental regions
Preventive service	Services where interaction with the carrier is detrimental to users	Defines sources as detrimental and sinks as valuable regions
Rivalness	Indicates whether service use does or does not deplete available quantity for other users	Rival use depletes the carrier weight available for “downstream” users; non-rival use does not
Limited or unlimited source, sink, use behavior	Source, sink, or use locations have either finite or infinite capacity to provide, deplete, or use a service	Determines whether source, sink, and use locations have limited or unlimited capacity to provide, deplete, or use a service
Flow routing type	Services move via specific routes (e.g., hydrologic or transportation networks, lines of sight, distance decay)	Determines the routes that carriers follow within the SPAN model
Source region	A location that supplies a carrier	Sources generate carrier agents for subsequent flow simulation
Sink region	A location that depletes the quantity of a carrier available for future use	Sinks deplete the carrier available for “downstream” users
Use region	The location of users – specific human beneficiary groups – on the landscape	Users benefit from or are damaged by interaction with a carrier

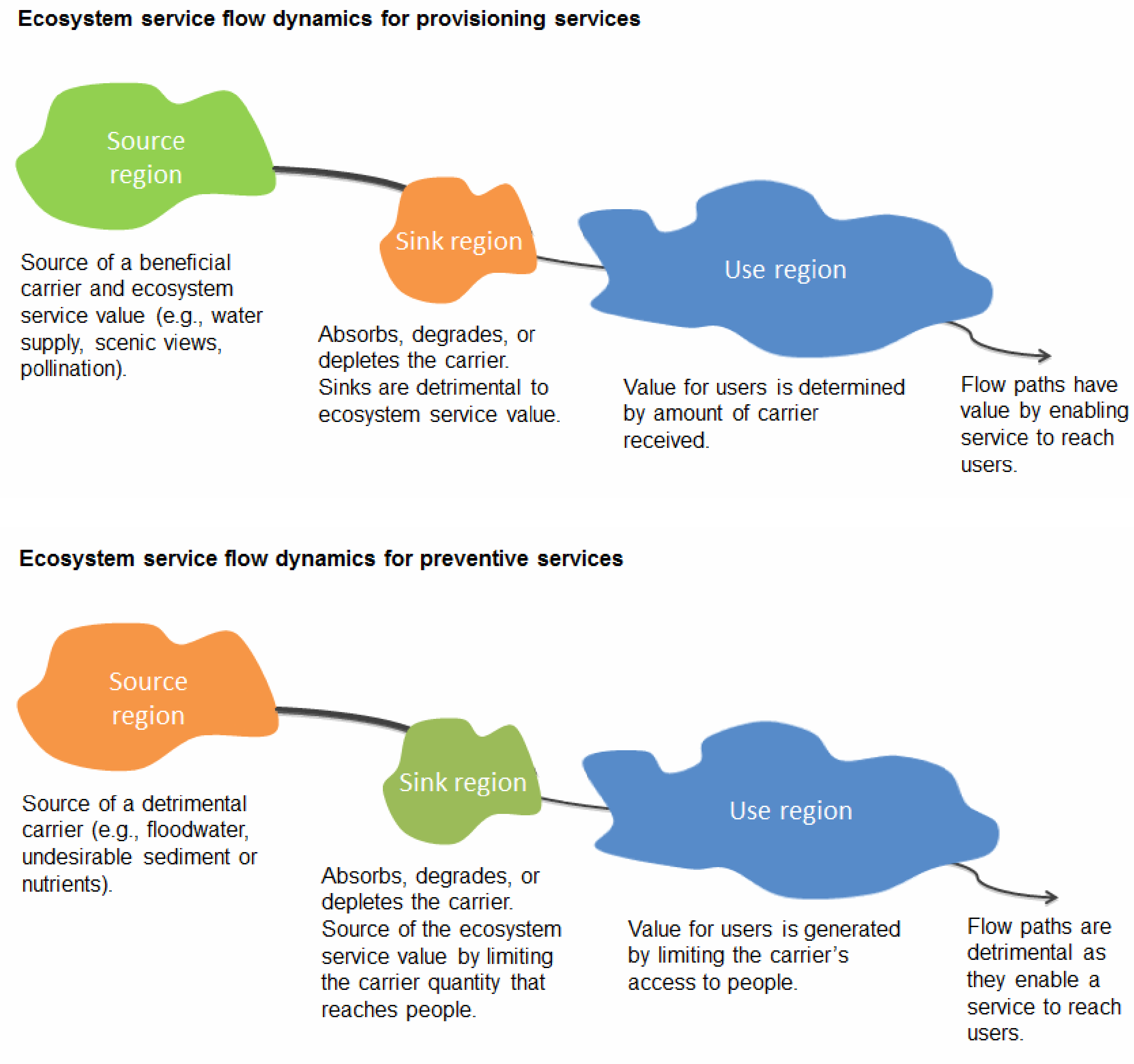
Flows	The spatially explicit routing of an ecosystem service from sources to users	Quantified and mapped flows, a major output of the SPAN model
Theoretical source, sink, use maps	*In situ* provision, depletion, or use of a service	Values calculated by the SPAN model without considering flows
Possible source, use, flow maps	Service dynamics when accounting for flows but not sinks	Values calculated by the SPAN model without considering sinks
Actual source, sink, use, flow maps	Service dynamics when accounting for sinks and flows	Values calculated by the SPAN model considering sinks and flows
Inaccessible source, sink, use maps	Service flows not delivered due to a lack of flow connections	Calculated by subtracting possible from theoretical values
Blocked source, use, flow maps	Service flows blocked by sinks	Calculated by subtracting actual from possible values

A beneficiary-based approach emphasizes spatially explicit identification of concrete beneficiary groups for modeling and valuation (Boyd and Banzhaf 2007, Fisher et al. 2008, Haines-Young and Potschin 2010, Nahlik et al. in press). This approach is consistent with recommendations to identify consistent sets of "final ecosystem goods and services" (Johnston and Russell 2011, Nahlik et al. in press). It also avoids the double counting problem by considering as ecosystem services only those processes that directly contribute to a benefit, not those processes that indirectly support other benefits.

An ecosystem service carrier is the means by which benefits flow from source or sink locations to use locations. Carriers can be conceptualized as buckets carrying defined quantities of a service as they move across the landscape. Flow paths, produced by the SPAN simulation algorithms, describe the carrier's movement and interaction with biophysical and human elements of the landscape. The carrier type differs for each service, and may represent matter (e.g. floodwater, CO2, fish biomass), information (e.g. relative rankings for culturally mediated services, aesthetic view quality, or proximity to valuable open space), or energy (e.g., wildfire).

If contact with a carrier is beneficial to people (e.g. scenic views, food, or drinking water), then a benefit is provided by ecosystems that generate and deliver the carrier to people. We refer to this class of ecosystem services as provisioning services, a definition that is distinct from the definition of provisioning services as the physical goods provided by ecosystems (MA 2005). If contact with the carrier is detrimental to quality of life (e.g. flood water, unwanted sediment or nutrients, disease, or wildfire), then ecosystems provide a service by preventing its flow to vulnerable human groups. We refer to this class of ecosystem services as preventive services. Thus for provisioning services, accumulation of the carrier by beneficiaries provides value, while for preventive services value is generated by limiting this accumulation (Figure 1). Some services may be either provisioning or preventive, depending on the human user: for example, excess sediment is detrimental for reservoir-based recreation and hydroelectric power generation, while in other cases sediment provides benefits, such as in maintaining soil fertility.

Figure 1: Ecosystem service flows for provisioning and preventive services.



To model the flow of a service as it moves across space, we must understand whether human use or contact with the carrier depletes the amount available for other users. These users may be located either physically downstream for hydrologic services or metaphorically “downstream” for other flow routing types. Rival use implies that beneficiaries who use a service leave less available for others (e.g., water used for irrigation is not available for others located downstream) while non-rival users do not (e.g., aesthetic views can be enjoyed regardless of how many people are there to watch).

For biophysically based services, sources, sinks, and users typically have a limited capacity to provide, deplete, or use the service. For example, wetlands that act as sinks of floodwater, sediment, or nutrients have a limited capacity to absorb these quantities from their carriers. Most consumptive water users require a finite amount of water to fulfill their needs. For some cultural services, such as aesthetic values, sources, sinks, and use are unlimited for practical purposes. A large mountain near an urban area can simultaneously provide views to a great number of beneficiaries. Similarly, visual blight can degrade sight lines for a large number of beneficiaries, and a single beneficiary could potentially enjoy a large number of high-quality views across a 360° viewing field.

The flow routing of different ecosystem services to people (or of people to service provision locations) can be characterized with greater precision than earlier attempts (Costanza 2008, Fisher et al. 2009) using a series of flow routing behaviors. Some ways in which carriers can move are through stream networks (e.g., riverine flood regulation, water supply, fluvial sediment regulation, nutrient regulation), lines-of-sight (viewsheds), or wave run-up models (coastal flood regulation). For some models, we apply a service-specific distance decay function to account for changes in value associated with increasing distance, such as open space proximity, pollinator access from habitat to agricultural fields, or existence value. In other cases, people move across a transportation network to access ecosystem goods, such as subsistence fisheries, or services, such as recreational activities. We can approximate these flows by using a shortest path algorithm that connects users to service provision locations via transportation routes.

2.1 Outputs from an ecosystem service flow model

Mapping ecosystem service flows begins with models and data describing the locations and quantities of potential ecosystem service provision (sources), human beneficiaries (users), and biophysical features that could deplete service flows (sinks). These components are measured in either physical units or relative rankings. Not all ecosystem services have sinks – for example, ecosystem goods and some types of cultural values do not have biophysical features that deplete their value. We apply the appropriate flow model (see below) to move carriers across the landscape using service-specific flow routing.

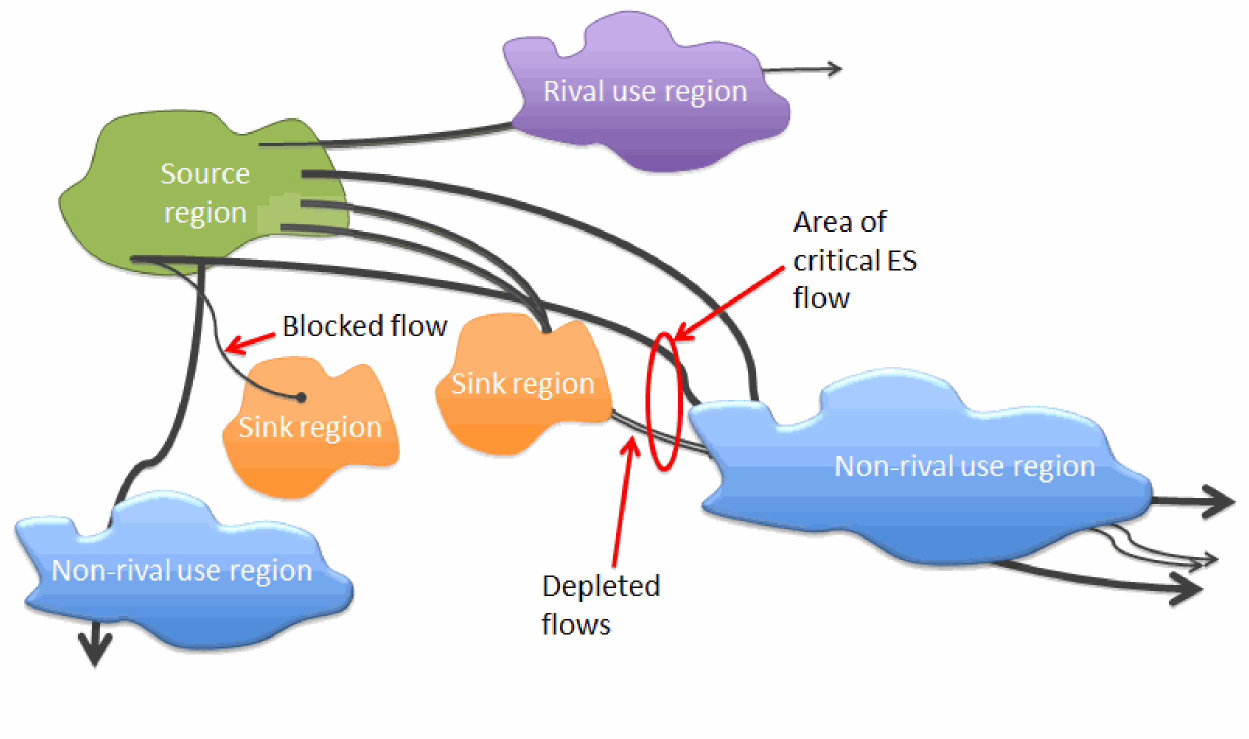
Running a flow model produces a series of spatially explicit results, which can be grouped into five categories to fully describe the spatial dynamics of ecosystem service flows:

1. *Theoretical source, sink, and use maps* quantify *in situ* source, sink, and use values without considering the flow of ecosystem services.
2. *Possible source, use, and flow maps* quantify the amount of the source that would reach users via flow paths *without considering the effects of sink locations*. Possible values represent the upper bound for service flows. Depending on the type of service being considered, the enhancement or removal of sinks could be used as a management strategy to increase the value of the ecosystem service.
3. *Actual source, sink, use, and flow maps* quantify the provision, depletion, use, and flows of the service when accounting for the effects of sinks.
4. *Inaccessible source, sink, and use maps* are calculated as the difference between theoretical and possible sources and uses, and theoretical and actual sinks. These maps identify source, sink, and use locations that are not physically connected via flow paths.
5. *Blocked source, use, and flow maps* are calculated as the difference between possible and actual values. These maps show lost sources, use, and flows due to sink effects.

For provisioning services, the flow model results provide use values showing met or unmet user demand. In these instances, sink features are detrimental, and source locations are valued based on the amount of the service they produce that is received by human beneficiaries. Because receipt of the service is desirable, the landscape features along flow paths that facilitate service transport from source to use locations also have value.

For preventive services, greater use indicates greater damage incurred due to encounters with the carrier. Locations with high source or flow values are undesirable as they may enable a carrier to reach people. Sinks that deplete the quantity of the detrimental carrier provide value to people (Figures 1-2).

Figure 2: Spatial dynamics of ecosystem services, mapping source, sink, and use regions and flows of services. The thickness of the arrow denotes the relative quantity of service flow, which is depleted by contact with a sink or rival use region.



Having developed the terminology to systematically describe and quantify ecosystem service flows, we provide a mathematical approach to flow quantification below.

3. The SPAN methodology

Service Path Attribution Networks (SPANs) are a family of models used to map ecosystem service flows, highlighting the spatial connections between source, sink, and use locations (see Johnson et al. 2010, 2012). SPAN use the concept of agent-based modeling, which investigates the emergent properties of a larger system by simulating the micro-level interactions of a set of individual actors located within it. The SPAN formalism uses three classes of agents: 1) carrier agents, which represent carrier quanta created at all source locations that move through the network following service-specific movement rules, 2) sink agents, which can reduce the quantity held by carrier agents upon encounter, 3) user agents, which benefit from or are harmed by encounters with the carrier and which, for rival services, can also reduce the quantity held by carrier agents. The SPAN algorithms initialize these agents from spatially explicit source, sink, and use values provided as inputs, and track the paths taken by carrier agents through the network to determine the quantity of services reaching users. The models follow three general steps described below.

3.1 Initializing the sink, user, and carrier agents

The first step in the SPAN algorithm is to create the sink, user, and carrier agents that will interact during the flow simulation. A sink agent is initialized at each sink location with an initial absorption capacity equal to the location's input sink value. Similarly, a user agent is created at each use location with the corresponding initial use level for the service, expressed as demand (for provisioning services) or vulnerability (for preventive services). Finally, a carrier agent with is initialized in each source location with the following attributes:

- **Actual Weight** (A): The quantity of a service carrier (measured in physical units or relative rankings) that each agent is transporting across the network. This is the initial source value at the agent's starting location.

- **Possible Weight** (P): The amount of the carrier that would be transported by the agent in the absence of sink effects. P - A, the sunk quantity, is particularly relevant when assessing preventive service flows. This is initially the same value as the actual weight A.

- **Route** (R): A list of the locations (l1, l2,… , ln), through which the carrier has traveled.

- **Sink Effects** (Q): A list of the sink locations encountered along the route R and the amount of the carrier absorbed in each during the simulation.

- **Use Effects** (X): A list of the use locations encountered along the route R and the amount of the carrier used in each during the simulation.

3.2 Mapping flow connections

The movement of carrier agents in SPAN is specified by the service-specific flow routing type, potentially modified by decay functions. The flow routing algorithm moves the carrier from location to neighboring location by examining the characteristics of each location and its immediate neighbors. The SPAN algorithm is equally suited for regular spatial grids and irregular polygons; spatial representations are chosen on a case-by-case basis based on the nature of the data and efficiency considerations. Different types of information may be required to inform the flow algorithms. For instance, elevation and stream network data are needed to route surface water, floodplain data are additionally needed to route floodwater, and road networks are needed to run transportation models.

At each step in the simulation, a carrier agent's flow path is extended by adding the just-encountered locations to its route list. The weights associated with these agents describe the amount of the carrier that follows each service trajectory, including any effects due to route branching. If a carrier agent moves into a location from which the routing algorithm cannot find a valid next step, flow routing ends for this agent, and any remaining weight is lost.

A decay function is also applied when appropriate. The decay function quantifies the reduction in the carrier quantity as a function of the distance it travels. For example, the view of an object generally becomes less valuable at greater distance. We represent this in SPAN by a function that converts initial weights to new decayed weights at the appropriate location along the flow route.

Finally, a transition threshold can optionally be set at a value > 0 as the minimum possible weight P that any carrier agent in the network must have in order to keep propagating the service. The transition threshold can be used to fine-tune model realism and run times on a case-by-case basis.

3.3 Analyzing the carrier memory

Each location in the SPAN simulation is assigned a "carrier memory" – a set of initially empty values that track sink, use, and flow values at that location. Once the flow model has run to completion, a given location's carrier memory will hold information about each agent and individual flow path that has led to it from any different source location on the landscape. The information can now be analyzed to determine the total amount of carrier each location has received from each producer, which sinks and rival use effects have blocked "downstream" access to the carrier, and what parts of the landscape exhibit the greatest flow density. All of these calculations are possible because each carrier agent holds not only its actual and possible weights and the sink and use effects encountered during the simulation but also the complete flow path traversed. The results of this path analysis are the series of maps described in Section 2. Translating the results of flow simulations into policy-relevant information is done differently according to the type of benefit provided (provisioning or preventive), the rival or non-rival character of the resource, the means of carrier quantification, and the flow routing type. We illustrate this through a description of use cases in Section 4.

4. Examples

We have currently formalized nine ecosystem service flow types using the SPAN framework: aesthetic viewsheds, open space proximity, surface water supply, riverine flood regulation, sediment regulation, coastal flood regulation, subsistence fisheries, recreation, and carbon sequestration and storage. Although these only account for a subset of the services listed in typical typologies (e.g., MA 2005), we believe they are sufficiently representative to serve as a basis for conceptualizing flows of other services. In this section, we describe flow functions for five representative families of services (Table 2). We describe the remaining four services, plus nine additional services that have not yet been formalized in SPAN, in the supporting online material.

Table 2. Flow characteristics for selected ecosystem services

Service	**Aesthetic viewsheds**	**Riverine flood regulation**
Benefit type	Provisioning	Preventive
Carrier/common units	Scenic quality (relative ranking, 0-100)	Runoff (mm/yr)
Scale	Viewshed	Watershed
Flow routing	Line of sight	Hydrologic flow
Decay	Inverse square	None
Rivalness	Nonrival	Nonrival
Source	Mountains, water bodies, etc.	Rainfall & snowmelt
Sink	Visual blight	Water absorbed by soil & vegetation
Use	Property/housing value	Economic assets in floodplains
Service	**Subsistence fisheries**	**Recreation**

Benefit type	Provisioning	Provisioning
Carrier/common units	Fish biomass (kg)	Recreational enjoyment (relative ranking, 0-100)
Scale	Walking distance to water	Travel distance
Flow routing	Walking simulation	Travel simulation
Decay	Gaussian	Weighted path costs
Rivalness	Rival	Nonrival but congestible
Source	Fishing grounds	Recreational areas suitable for a given activity
Sink	None	None
Use	Subsistence communities near fisheries	Recreationists interested in a given activity
Service	**Carbon sequestration & storage**	
Benefit type	Provisioning	
Carrier/common units	CO_2 absorbed/emitted (tons/yr)	
Scale	Global	
Flow routing	Global atmospheric mixing	
Decay	None	
Rivalness	Rival	
Source	Vegetation & soil C sequestration	
Sink	Stored C release (fire, land use change)	
Use	CO_2 emitters	

4.1 Aesthetic viewsheds

The viewsheds SPAN model uses lines of sight to connect and quantify view paths between source locations (visually valued objects) and use locations (areas of potential enjoyment, such as housing), check for obstructions and sink features (visual blight), and determine, using a digital elevation model (DEM), how much of the source can be seen from a given use location. The source, sink, and use inputs give relative rankings for sources, sinks, or users of visually valued viewsheds. Sink features that can degrade viewsheds are accounted for only if they are present in the foreground of a user's view of a source location. A distance decay function is applied to compute the visual utility originating from the source location that reaches each user.

The viewshed model can also be used as an input to recreation models described below, to map visually significant locations for recreation. An independent open space proximity model similarly maps values for open space quality and quantity plus the location of housing but models flows using a Gaussian distance decay function rather than lines of sight.

4.2 Riverine flood regulation

The riverine flood regulation SPAN model traces the path taken by runoff downhill, downstream, and onto floodplains according to a digital elevation model (DEM) and stream network and floodplains data. The source values represent the total expected runoff volume per location over the time period of the simulation. Sink values quantify the expected water absorption capacity of each location. Users are mapped as human settlements or other assets that could be harmed by floodwater. As floodwater carrier agents move from location to location, their weight (the remaining runoff value) is reduced by encounters with sinks, but not by users. Users in floodplains that are in the path of floodwater will be affected proportionally to the floodwater volume that reaches them.

Surface water supply, sediment regulation, and nutrient regulation models model flows in similar ways, but are in some cases provisioning services (water supply and some instances of sediment regulation). Coastal flood regulation acts similarly but uses a wave run-up model rather than flow through stream networks as its flow routing type.

4.3 Subsistence fisheries

The subsistence fisheries SPAN model simulates the near-shore, rival fishing behavior of non-commercial fishermen located near major water bodies. Source locations record the fish biomass available over the time period of the simulation. Use locations identify fish-dependent settlements and assign them individual demand values in the same units as the source values. Roads and trails connect fishermen to their nearest viable fishing grounds. No sinks effects are included in this model. This approach could be extended for modeling subsistence use of other ecosystem goods based on resource access.

4.4 Recreation

Our recreation models currently map expected relative site quality for different activities (e.g., hiking, canoeing, birding, hunting, wildlife viewing) based on ecosystem attributes and site access. Recreational service flows (i.e., choice of and travel to recreational sites) are based on human preferences for particular activities and locations, perceptions of places capable of providing suitable and desirable settings for that activity, and transport pathways (e.g. roads, trails) that link the origin and destination locations. This adds a great deal of complexity to flow modeling, as preferences are shaped by past experiences and place attachment, as well as distance, travel networks, and possible means of travel. To fully understand recreation use and flows, future applications will explore the use of choice models (e.g., random utility models) and transportation network models where good visitor use and origin data are available.

4.5 Carbon sequestration and storage

The carbon SPAN model computes the mass of carbon sequestered and stored that is available to offset anthropogenic carbon emissions produced within the same region. Before being distributed to use locations, this sequestration value is first reduced by landscape-generated carbon emissions (e.g., release of stored carbon due to fire or deforestation).

While computing carbon sequestration and storage may be sufficient for many applications, the identification of flow paths allows users to compute regional carbon budgets by interpreting human carbon emitters as users of carbon sequestration, with carbon-emitting ecosystems as sinks in the flow model. Because all source locations (carbon sequestering ecosystems) are connected to all sink and use locations by fast atmospheric mixing, the standard SPAN approach of tracking explicit routes from source to use locations is not adopted here. Instead, the algorithm simply distributes the remaining source value from each location among all use locations based on their relative emissions values. This example shows how quantifying service provision and use can be informative even when the spatial component of an ecosystem service flow is diffuse and can be assumed instantaneous.

5. **Applying ecosystem service flow concepts**

The SPAN algorithm was designed as a component of the ARIES modeling platform (ARIES 2012). While ARIES currently supports modeling flows for nine ecosystem services across 10 case study regions, improvements under development will enhance its versatility as well as the scientific quality and policy relevance of its outputs. System improvements include an encoded set of artificial intelligence-based decision rules that enable specific model components to be automatically selected under appropriate circumstances (e.g., to include different model influences for specific biomes, under certain climatic regimes, or above specified population or income thresholds). This “intelligent” modeling infrastructure (Villa 2009) is capable of selecting basic ecosystem service assessment models for regions with limited data or model availability, complimented in case study regions by locally calibrated models that are more sensitive to regionally specific factors and can make use of higher-quality data.

To date, the source, sink, use, and flow models developed in ARIES have largely been developed from literature reviews and discussions with regional experts. In many cases the realism of the results, including those of the flow models, could be improved by incorporating previously developed biophysical models that have undergone extensive peer review. As the ARIES model base is extended, incorporation of external models will become increasingly possible, with ARIES' automated model selection mechanism playing a larger role in simplifying their use for the end user.

Of the SPAN models developed thus far, we ascribe relatively greater confidence to the quality of model outputs for carbon, aesthetics, and fisheries. Several types of ecosystem service flow models – for hydrologic services, recreation, and commercial ecosystem goods – present special challenges that we discuss below. While others have also proposed agent-based modeling approaches in hydrology (Reaney 2008), serious limitations on spatially explicit data for hydrologic processes such as precipitation, snowmelt, and soil moisture have restricted traditional hydrologic modeling to producing results at the watershed or sub-watershed scale. These limitations are more pronounced at finer temporal scales needed to model seasonal water supply or event-based flood, sediment, or nutrient flows. Additionally, high-quality water-use data are often lacking. New efforts such as the U.S. Department of Interior's WaterSMART initiative (U.S. DOI 2012), which is mapping and modeling hydrologic processes and water use at fine spatial and temporal scales to address potential water conflicts, could provide data to increase our confidence in use of agent-based hydrologic models at fine spatial and temporal scales.

Data limitations, the complexity of human behavior, and the interaction between natural capital and built infrastructure increase the difficulty of modeling the spatial dynamics of ecosystem service flows for recreation. Thus far, our work to model recreational values in ARIES has been limited to quantifying relative site quality for various recreational activities (e.g., hiking, canoeing, birdwatching, hunting, wildlife viewing). In some cases, high-quality data sources (e.g., Park Studies Unit 2012) may support future modeling of recreational use and flows using park-specific distance decay functions for visitation.

Lastly, we have not attempted to model flows of commercial ecosystem goods through trade networks. Our treatment of ecosystem goods has thus far been limited to water supply and subsistence resource use, which can be modeled through hydrologic flows and transportation simulation models, respectively. While models to link consumers to sources of commercial goods generated by ecosystems could improve the transparency of resource use and consumer choices, we have not yet explored the data and models needed to map and understand such linkages.

Like other spatially explicit ecosystem service modeling tools, ARIES is capable of quantifying ecosystem service changes under alternative scenario conditions. We are currently working to quantify the differences between theoretical and actual ecosystem service flows under alternative scenarios and draw distinctions between the two that could better inform their appropriateness in decision making. Theoretical values may be useful in identifying a region's carrying capacity related to a particular service, while actual values represent the value of service delivery to existing users. We are also exploring how the outputs from ecosystem service flow models can inform improved approaches to spatially explicit valuation using a range of techniques, including but not limited to value transfer (Wilson and Hoehn 2006). Finally, we are working to highlight which source, sink, use, and flow maps are most informative to decision makers for each ecosystem service, in order to provide ecosystem service flow information that is as parsimonious and policy-relevant as possible.

5.2 Ecosystem service flow quantification in other systems

A variety of ecosystem services modeling tools have undergone development in recent years (BSR 2011, Bagstad et al. in press). Such tools can make use of SPAN-based flow modeling in three ways. First, the outputs of some models could be used as source, sink, or use input data directly linked to SPAN models inside of ARIES, allowing other models to supplement the existing ARIES model library. Second, since the SPAN code is open source, other modelers could incorporate it into their own modeling systems. Third, for modeling systems that already calculate ecosystem service flows (e.g., the InVEST hydrology, pollination, and viewshed models, Kareiva et al. 2011) but do not report flow results in a complete or consistent manner, using the flow concepts presented in section 2 of this paper could lead to more comprehensive and theoretically consistent communication of ecosystem service flow information.

5.3 Policy implications

Understanding how services flow across the landscape from ecosystems to people has been a major research priority and a barrier to accurately valuing service flows for policy (Tallis et al. 2008). In the absence of quantified flows, ecosystem service valuation is based on the potential for an ecosystem to provide a service, instead of the actual value it supplies. With flows quantified and mapped, we can understand when an ecosystem is actually delivering benefits to distinct beneficiary groups. A more complete accounting for the spatial mismatch between source and use locations makes a much stronger case to managers and stakeholders by showing how and to whom a specific piece of land delivers a specific type of benefit. Therefore the impacts of a decision to alter the landscape become much more tangible as service values or degradation can be attributed to specific landowners.

Quantified ecosystem service flow information allows decision makers to plan interventions and policy more precisely to minimize loss of important services, or develop plans for restoring or enhancing impaired ecosystem services. For instance, depending on the service and ecological, socioeconomic, and institutional setting, approaches could be designed to 1) increase beneficiaries' ability to use a service that flows to them, 2) change service flows to users by increasing or decreasing the effects of sinks along flow paths, or 3) redirect flow paths to route inaccessible or blocked service values to more potential users (Villa et al. 2011). Flow analysis determines not only the accrued value to each beneficiary, but also the amount of service provision unable to reach beneficiaries due to the spatial mismatch in source and use locations. Additionally, model results can highlight critical pathways (i.e., places where multiple flows converge in high density or where single flows transmit all of the service received by a group of beneficiaries). These locations will be valuable for protecting access to services, as will protection of the source or sink locations from which services originate.

5.4 Interpreting flow model outputs

One of the primary obstacles in using ecosystem service flow information in science and decision making is the lack of a common language between model developers and resource management professionals. The inherent complexity of mapping ecosystem service flows and our efforts to expand the state of the science has led to new terminology to describe the flow modeling process and results. As the science of ecosystem services continues to evolve and practitioners become more familiar with these underlying concepts, we anticipate that the difficulties associated with describing flow modeling approaches, model results, and policy implications will decline.

The SPAN models produce a series of maps that are useful in specific decision contexts. The first group of maps helps understand how much service value is available and how much room there is for improvement. Theoretical value maps show the amount of value that could be produced in ideal situations, assuming that all services produced are able to reach people. Possible value maps show the amount of the service that could reach beneficiaries, accounting for supply (source locations), rival use, and connectivity (flow paths), but assuming there are no sinks present on the landscape. Actual value maps depict the amount of a service that reaches users after accounting for supply, rival use, depletion, and connectivity. A comparison of these maps can be used to understand the efficiency of service flows in the area: if the possible values are higher than the actual values, there may be room for policy interventions to improve or restore service flows.

Other maps link supply and demand in ways that may be used to spot problem areas in need of intervention. Blocked value maps reveal services that are produced by ecosystems but cannot get to people, because of issues such as pollution or flow capture by infrastructure or natural landscape features. Inaccessible value maps highlight services produced by an ecosystem that cannot be accessed by beneficiaries due to a lack of connectivity between source and use locations. Blocked value maps can be used to prioritize areas where human intervention might restore service flows, while inaccessible value maps highlight those areas where service production may be under-utilized due to current flow connectivity.

Result maps are always produced in pairs, describing both the ecosystem provision and human use of the service. Depending on the research or decision-making priorities, one or the other may be more relevant. For example, a blocked use map for surface water will show the location and amounts of unmet water demand (e.g. locations without access to water) for a specific beneficiary group. Conversely, the blocked source map shows areas that produce water that is lost to evapotranspiration, caught by infrastructure such as dams, or polluted beyond the point of usability. The inaccessible source map shows water sources that cannot meet the needs of beneficiaries without major structural intervention on the landscape (altering flow dynamics to produce connectivity). With proper guidance, a decision maker could learn to design scenarios and use a combination of flow model output maps to gain a deeper understanding of the service values provided, the extent of policy opportunities and limitations, and the location and quantity of demand, both met and unmet, for various stakeholder groups across a range of social, policy, and environmental conditions.

5.5 Conclusions

In this paper we have described the underlying concepts, structure, and implications of the SPAN framework for quantifying ecosystem service flows. By representing the landscape as a system of source, sink, and use locations connected by a flow network, this approach can draw on a wide range of data aggregation techniques to match the scale of the assessment to the flow characteristics of the service under study. Because carrier weights and the sink and rival use effects on them may be represented probabilistically, uncertainty about the strength of these service flows can also be made explicit in the simulation results. The model's benefit-based focus, measuring service flows from ecosystems to people, could support more accurate spatially explicit valuation (monetary or non-monetary) than approaches that quantify in situ service provision alone. The provision and use relationships between specific locations are clearly identified as are beneficial or detrimental effects on service flows from both landscape features and human use.

In cases where different beneficiary groups compete for a finite resource, flow paths can clarify which groups have the earliest and/or easiest access. For preventive services, the SPAN model's distinction between possible and actual carrier weights makes it possible to estimate how much flow (representing potential threats) each sink location blocks from reaching each use location. Finally and perhaps most interestingly, mapping the flow densities for particular services opens the door to novel approaches to managing landscapes for ecosystem services. Rather than planning just to protect ecosystems which appear to provide services, ecosystem service science can begin to support more holistic conservation and development planning that accounts for service providers, sink locations, and the flow corridors needed to transmit these benefits to human users.

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