Ecosystem Services ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at SciVerse ScienceDirect

Ecosystem Services

journal homepage: www.elsevier.com/locate/ecoser

Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services

Kenneth J. Bagstad [a,*], Gary W. Johnson [b], Brian Voigt [b], Ferdinando Villa [c]

[a] US Geological Survey, Rocky Mountain Geographic Science Center, Denver, CO, USA
[b] Gund Institute for Ecological Economics, University of Vermont, Burlington, VT, USA
[c] Basque Center for Climate Change (BC3), IKERBASQUE, Basque Foundation for Science, Spain

ARTICLE INFO

Article history:
Received 15 April 2012
Received in revised form
12 July 2012
Accepted 16 July 2012

Keywords:
Ecosystem services
Spatial flows
Beneficiaries
Service Path Attribution Network (SPAN)
Artificial Intelligence for Ecosystem Services (ARIES)

ABSTRACT

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 benefit is supplied by an ecosystem's provision of a beneficial flow to people or by absorption of a detrimental flow before it reaches them. 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.

1. Introduction

1.1. Problems in defining and mapping ecosystem service flows

Since the earliest formalizations of the ecosystem services concept (King, 1966; Helliwell, 1969), scientists have constructed lists of ecosystem services. The Millennium Ecosystem Assessment (2005) has achieved perhaps the greatest scientific consensus of these in recent years, but still faces notable limitations. Soon after its publication some argued that a stronger focus on the beneficiaries of ecosystem services was a prerequisite to deal 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., 2012). Others 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).

Treatment of ecosystem services in ecology and economics both date back to at least the 1960s (Coase, 1960; King, 1966; Krutilla, 1967; Helliwell, 1969), and while challenges remain in the underlying ecology and economics of ecosystem services, an even more basic set of geographic questions — "where are ecosystems producing benefits" and "who and where are people using ecosystem services" — too often remains unanswered in the field of ecosystem services.

Tallis et al. (2008) summarized this problem: "The science of ecology made huge advances when it began to consider dispersal and the importance of movement in governing the dynamics of ecological communities. However, the science of ecosystem services has not yet made this transformation, and as a result typically depicts ecosystem services as site-bound on static maps." To date no systematic solution to this problem has been proposed. 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 patterns of transmission of a service from provision to benefit areas,

* Corresponding author. Tel.: +1 303 202 4136.
E-mail address: kjbagstad@usgs.gov (K.J. Bagstad).

2212-0416/$ - see front matter © 2012 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.ecoser.2012.07.012

reflecting the understanding that ecosystems and their beneficiaries are often not co-located. However, these contributions do not provide systematic, quantitative tools to measure and map ecosystem service flows.

The inability to consistently describe, quantify, and map ecosystem service flows limits 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 provide 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, pollination, and services provided by migratory species, Kareiva et al., 2011; Semmens 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 paper, we use it to refer to the transmission of a service from ecosystems to people. Alternatively, the term is often used to describe the annual flow of benefits accruing to people as generated by stocks of ecosystem structure (Daly and Farley, 2004). Such semantic inconsistency remains problematic across the field of ecosystem services.

1.2. Objectives

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., 2011; ARIES, 2012). However, the flow modeling formalization presented here can apply more generally to the quantification of ecosystem service flows.

We first describe the concepts needed to communicate the spatial dynamics of ecosystem services (Section 2). In Section 3 we describe the Service Path Attribution Network (SPAN; Johnson et al., 2012) algorithm that generalizes the ecosystem services flow problem. In Section 4, we provide examples of the SPAN formalization 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. As Supporting online material, we include a detailed description of the currently implemented SPAN models and examples of how to apply this approach to additional ecosystem services.

2. Concepts to operationalize ecosystem service flows

Imagine a flow of floodwater moving down a river valley, or of visitors to a natural area that provides some recreational amenity. How can we quantify supply, demand, and flows for these very different services in a theoretically and quantitatively consistent manner? Such an approach requires five key elements (summarized with additional below-described concepts in 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 simulation proceeds by using data and models to 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); the SPAN algorithms connect these areas to quantify service flows.

A *beneficiary-based approach* emphasizes identification of spatially explicit, concrete beneficiary groups for modeling and valuation (Boyd and Banzhaf, 2007; Fisher et al., 2008; Haines-Young and Potschin, 2010; Nahlik et al., 2012). This approach is consistent with recommendations to identify consistent sets of "final ecosystem goods and services" (Johnston and Russell, 2011; Nahlik et al., 2012). It also avoids the double counting problem by considering ecosystem services to be 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 are treated as the *agents* in the SPAN algorithm (described in Section 3), and can be conceptualized as buckets carrying defined quantities of a service as they move across the landscape. Flow paths, produced by the SPAN simulation, describe the carrier's movement and interaction with biophysical and human elements of the landscape (e.g., through hydrologic or transportation networks or the atmosphere) but are not themselves depleted by sinks. Carrier types differ for each service, and may represent matter (e.g., floodwater, CO_2, fish biomass), information (e.g., relative rankings for culturally mediated services such as 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 these as *provisioning benefits*. 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 benefit by preventing that flow to vulnerable human groups. We refer to these as *preventive benefits*. Thus provisioning benefits are provided through accumulation of the carrier by beneficiaries, while preventive benefits are generated by limiting this accumulation (Fig. 1). Some ecosystem services encompass benefits that are either provisioning or preventive, depending on the human user: for example, excess sediment is detrimental for reservoir-based recreation and hydroelectric power generation, but in some cases sediment provides benefits, such as in maintaining soil fertility in agricultural fields. Although the MA's (2005) well-known classification of ecosystem services uses the similar term *provisioning services*, we are not seeking to classify *services* like the MA when we distinguish between provisioning and preventive benefits, but instead classify flow behaviors for the purposes of better quantifying how ecosystems provide benefits to people.

To model the flow of a service as it moves across space, we must also 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

Please cite this article as: Bagstad, K.J., et al., Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services. Ecosystem Services (2012), http://dx.doi.org/10.1016/j.ecoser.2012.07.012

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 benefit	Benefits provided through delivery of a beneficial carrier to users	Defines sources as valuable and sinks as detrimental regions
Preventive benefit	Benefits provided through absorption of a detrimental carrier before it reaches 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 later 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	Outputs calculated by the SPAN model without considering flows
Possible source, use, flow maps	Service dynamics when accounting for flows but not sinks	Outputs calculated by the SPAN model without considering sinks
Actual source, sink, use, flow maps	Service dynamics when accounting for sinks and flows	Outputs 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 outputs
Blocked source, use, flow maps	Service flows blocked by sinks	Calculated by subtracting actual from possible outputs

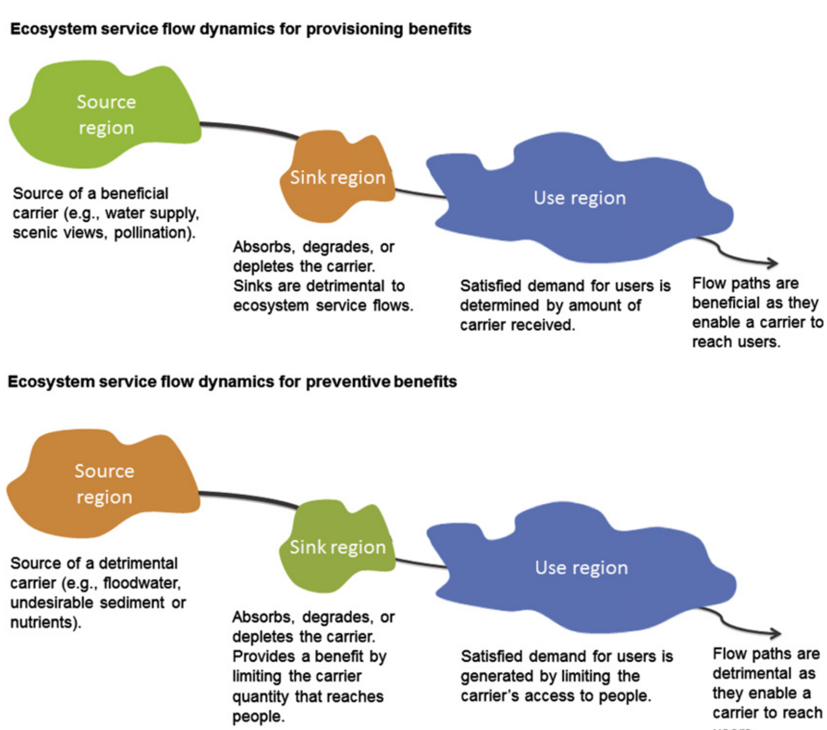

Fig. 1. Ecosystem service flows for provisioning and preventive benefits.

Please cite this article as: Bagstad, K.J., et al., Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services. Ecosystem Services (2012), http://dx.doi.org/10.1016/j.ecoser.2012.07.012

people are there to watch, though recreational use of a site can be congestible).

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 could 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 efforts (Costanza, 2008; Fisher et al., 2009) using a series of flow routing behaviors. Carriers can move through stream networks (e.g., riverine flood regulation, water supply, fluvial sediment regulation, nutrient regulation), lines-of-sight (viewsheds), or wave run-up (coastal flood regulation). For some models, we apply a service-specific distance decay function to account for changes in flows 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 such 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

To map ecosystem service flows, we begin with models and data to map the locations and quantity of potential ecosystem service provision (sources), human beneficiaries (users), and biophysical features that can 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 flows. We apply the appropriate flow model (Sections 3 and 4) 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 sources, sinks, and use 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*. These 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 flow 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.

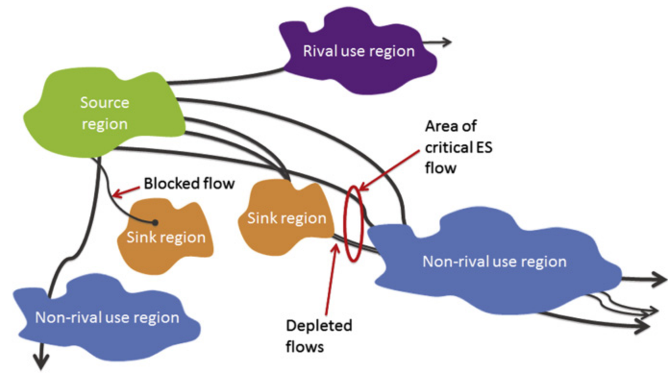

Fig. 2. Spatial dynamics of ecosystem services, mapping source, sink, and use regions and flows of services. The thickness of the arrow denotes the relative quantity of service flow, which is depleted by contact with a sink or rival use region.

5. *Blocked source*, *use*, *and flow maps* are calculated as the difference between possible and actual sources, uses, or flows. These maps show lost sources, use, and flows due to depletion by sinks.

For provisioning benefits, the flow model results quantify met or unmet user demand. In these instances, sink features are detrimental, and source locations provide a benefit 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 are also critical to benefit provision.

For preventive benefits, greater use indicates greater damage incurred due to encounters with the carrier. High source or flow locations are undesirable as they may enable a carrier to reach people. Sinks that deplete the quantity of the detrimental carrier provide benefits to people (Figs. 1 and 2).

Because sources and flow routes provide provisioning benefits while sinks provide preventive benefits, different types of maps will have different implications for valuation and decision making. We discuss this further in Section 5.4. Having developed the terminology to systematically describe and quantify ecosystem service flows, we next describe a mathematical approach to flow quantification.

3. The SPAN algorithm

Service Path Attribution Networks (SPANs) are a family of agent-based models used to map ecosystem service flows, highlighting the spatial connections between source, sink, and use locations (see Johnson et al., 2012 and the Supporting online material for a formal description of the algorithms). Agent-based models investigate 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, and (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 data, 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 benefits) or vulnerability (for preventive benefits). Finally, a carrier agent is initialized in each source location with the following attributes:

1. 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.
2. 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 benefit flows. This is initially the same value as the actual weight A.
3. Route (R): a list of the locations ($l_1, l_2, \ldots, l_n$), through which the carrier has traveled.
4. 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.
5. 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 (Fig. 3). 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 and levee 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 carrier quantity 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 some objects 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.

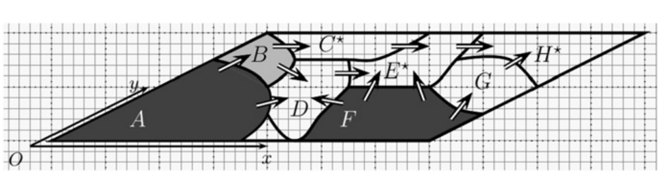

Fig. 3. A raster-based landscape segmented into source, sink, and use regions. Each region corresponds to a location in the SPAN, and the arrows show the direction of service flow between regions. A and F are source regions, B is a sink region, C, E, and H contain potential users, denoted by an asterisk.

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 time on a case-by-case basis.

3.3. Analyzing the carrier cache

Each location in the SPAN simulation is assigned a "carrier cache"—a set of initially empty values that track sink, use, and flow quantities at that location. Once the flow model has run to completion, a given location's carrier cache will hold information about each agent and individual flow path that has led to it from any different source location on the landscape. That 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 2.1.

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.

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.

Table 2
Flow characteristics for selected ecosystem services.

Service	**Aesthetic viewsheds**	**Riverine flood regulation**
Benefit type	Provisioning	Preventive
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 and vegetation
Use	Property/housing value	Economic assets in floodplain
Service	**Subsistence fisheries**	**Recreation**
Benefit type	Provisioning	Provisioning
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 and storage**	
Benefit type	Provisioning	
Units	CO_2 absorbed/emitted (tons/yr)	
Scale	Global	
Flow routing	Global atmospheric mixing	
Decay	None	
Rivalness	Rival	
Source	Vegetation and soil C sequestration	
Sink	Stored C release (fire, land use change)	
Use	CO_2 emitters	

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 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 DEM and stream network and floodplains data. The source data represent the total expected runoff volume per location over the time period of the simulation. Sinks 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) 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 quantify flows in similar ways, but are in some cases provisioning benefits (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. 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, crowding and displacement, and roads or 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, sequestration is first reduced by landscape-generated carbon emissions (e.g., release of stored carbon due to fire or deforestation).

Carbon emissions can of course be offset anywhere on Earth. Computing carbon sequestration and storage may thus be sufficient for many applications. However, flow quantification 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 quantity from each location among all use locations based on their relative emissions. 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

5.1. Ecosystem service flow quantification in ARIES: next steps

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 production of results at the watershed or subwatershed 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 (US 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, complex 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 quantification of 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 results may be useful in identifying a region's carrying capacity related to a particular service, while actual results represent the benefit flow delivered 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 data directly input 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 flow it supplies. With flows quantified and mapped, we can understand when an ecosystem

Please cite this article as: Bagstad, K.J., et al., Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services. Ecosystem Services (2012), http://dx.doi.org/10.1016/j.ecoser.2012.07.012

is actually delivering benefits to distinct beneficiary groups, providing a more sound basis for economic valuation. 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 delivery 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 services to more potential users (Villa et al., 2011). Flow analysis determines not only the accrued benefit 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—those 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 benefits 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 have 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 to understand *how much of a service is available and how much room there is for improvement. Theoretical service maps* show the amount of benefit that could be produced in ideal situations, assuming that all services produced are able to reach people. *Possible service 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 service 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 benefits are greater than the actual benefits, 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 service 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 service 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 service maps can be used to prioritize areas where human intervention might restore service flows, while inaccessible service 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 benefits 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.

6. 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 benefit 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 benefit 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 benefits, 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.

Acknowledgments

Partial support for this paper was provided by the USGS Mendenhall Postdoctoral Research Program and Grant no. 9982938 from the US National Science Foundation. An initial marine component was funded by UNEP-WCMC. We thank the

ARIES partner organizations, Conservation International (CI) and Earth Economics (EE) and the many collaborators at case study locations for support, data and knowledge sharing, and contributing to improving the understanding of regional ecosystem service dynamics. We thank Jay Diffendorfer and two anonymous reviewers for helpful comments on an earlier draft of this manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ecoser.2012.07.012.

References

ARIES, 2012. ARIES: Artificial Intelligence for Ecosystem Services. Available from: 〈http://www.ariesonline.org〉 (accessed 14.04.12).

Bagstad, K.J., Semmens, D., Winthrop, R., Jaworski, D., Larson, J. Ecosystem Services Valuation to Support Decision-Making on Public Lands: A Case Study for the San Pedro River, Arizona. USGS Scientific Investigations Report, Reston, VA, in press.

Boyd, J., Banzhaf, S., 2007. What are ecosystem services? The need for standardized environmental accounting units. Ecological Economics 63, 616–626.

BSR Environmental Services, Tools, and Markets Working Group, 2011. New Business Decision-Making Aids in an Era of Complexity, Scrutiny, and Uncertainty: Tools for Identifying, Assessing, and Valuing Ecosystem Services. BSR, San Francisco, CA.

Chan, K.M.A., Shaw, M.R., Cameron, D.R., Underwood, E.C., Daily, G.C., 2006. Conservation planning for ecosystem services. PLoS Biology 4 (11), 2138–2152.

Coase, R., 1960. The problem of social cost. The Journal of Law and Economics 3 (1), 1–44.

Costanza, R., 2008. Ecosystem services: multiple classification systems are needed. Biological Conservation 141 (2), 350–352.

Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Ricketts, T.H., Salzman, J., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Frontiers in Ecology and the Environment 7 (1), 21–28.

Daly, H.E., Farley, J., 2004. Ecological Economics: Principles and Applications. Island Press, Washington, DC.

Eade, J.D.O., Moran, D., 1996. Spatial economic valuation: benefits transfer using geographical information systems. Journal of Environmental Management 48, 97–110.

Fisher, B., Turner, K., Zylstra, M., Brouwer, R., de Groot, R., Farber, S., Ferraro, P., Green, R., Hadley, D., Harlow, J., Jefferiss, P., Kirkby, C., Morling, P., Mowatt, S., Naidoo, R., Paavola, J., Strassburg, B., Yu, D., Balmford, A., 2008. Ecosystem services and economic theory: integration for policy-relevant research. Ecological Applications 18 (8), 2050–2067.

Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecological Economics 68, 643–653.

Haines-Young, R., Potschin, M., 2010. Proposal for a Common International Classification of Ecosystem Goods and Services (CICES) for Integrated Environmental and Economic Accounting (V1). Report to the European Environment Agency. Centre for Environmental Management, University of Nottingham, Nottingham, UK.

Helliwell, D.R., 1969. Valuation of wildlife resources. Regional Studies 3 (1), 41–47.

Johnson, G., Bagstad, K.J., Snapp, R., Villa, F., 2012. Service Path Attribution Networks (SPANs): a network flow approach to ecosystem services assessment. International Journal of Agricultural and Environmental Information Systems 3 (2), 54–71.

Johnston, R.J., Russell, M., 2011. An operational structure for clarity in ecosystem service values. Ecological Economics 70, 2243–2249.

Kareiva, P., Tallis, H., Ricketts, T.H., Daily, G.C., Polasky, S. (Eds.), 2011. Natural Capital: Theory and practice of mapping ecosystem services. Oxford University Press, Oxford.

King, R.T., 1966. Wildlife and man. The New York State Conservationist 20 (6), 8–11.

Krutilla, J.V., 1967. Conservation reconsidered. The American Economic Review 57 (4), 777–786.

Millennium Ecosystem Assessment (MA), 2005. Millennium Ecosystem Assessment: Living Beyond Our Means—Natural Assets and Human Well-Being. World Resources Institute, Washington, D.C.

Nahlik, A.M., Kentula, M.E., Fennessy, M.S., Landers, D.H., 2012. Where is the consensus? A proposed foundation for moving ecosystem service concepts into practice. Ecological Economics 77, 27–35.

Park Studies Unit, University of Idaho, 2012. National Park Service–Visitor Services Project. Available from: 〈http://www.psu.uidaho.edu/vsp.htm〉 (accessed 06.04.12).

Reaney, S.M., 2008. The use of agent based modelling techniques in hydrology: determining the spatial and temporal origin of channel flow in semi-arid catchments. Earth Surface Processes and Landforms 33, 317–327.

Ruhl, J.B., Kraft, S.E., Lant, C.L., 2007. The Law and Policy of Ecosystem Services. Island Press, Washington, DC.

Semmens, D.J., Diffendorfer, J.E., Lopez-Hoffman, L., Shapiro, C.D., 2011. Accounting for the ecosystem services of migratory species: quantifying migration support and spatial subsidies. Ecological Economics 70, 2236–2242.

Tallis, H., Kareiva, P., Marvier, M., Chang, A., 2008. An ecosystem services framework to support both practical conservation and economic development. Proceedings of the National Academy of Sciences of the United States of America 105 (28), 9457–9464.

Troy, A., Wilson, M.A., 2006. Mapping ecosystem services: practical challenges and opportunities in linking GIS and value transfer. Ecological Economics 60, 435–449.

US Department of the Interior (DOI), 2012. WaterSMART Clearinghouse. Available from: 〈http://www.doi.gov/watersmart/html/index.php〉 (accessed 06.04.12).

Villa, F., 2009. Semantically-driven meta-modelling: automating model construction in an environmental decision support system for the assessment of ecosystem services flow. In: Athanasiadis, I.N., et al. (Eds.), Information Technology in Environmental Engineering. Springer, New York, NY, pp. 23–36.

Villa, F., Bagstad, K.J., Johnson, G., Voigt, B., 2011. Scientific instruments for climate change adaptation: estimating and optimizing the efficiency of ecosystem services provision. Economia Agraria y Recursos Naturales 11 (1), 83–98.

Wallace, K.J., 2007. Classification of ecosystem services: problems and solutions. Biological Conservation 139, 235–246.

Wilson, M.A., Hoehn, J.P., 2006. Valuing environmental goods and services using benefit transfer: the state of the art and science. Ecological Economics 60, 335–342.