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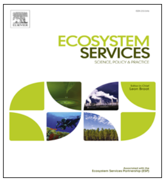

Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services

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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.

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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,

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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

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