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A quantitative framework for assessing spatial flows of ecosystem services☆

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ABSTRACT

Spatial disconnections between locations where ecosystem services are produced and where they are used are common. To date most ecosystem service assessments have relied on static indicators of provision and often do not incorporate relations with the corresponding beneficiaries or benefiting areas. Most studies implicitly assume spatial and temporal connections between ecosystem service provision and beneficiaries, while the actual connections, *i.e.*, ecosystem service flows, are poorly understood. In this paper, we present a generic framework to analyze the spatial connections between the ecosystem service provisioning and benefiting areas. We introduce an indicator that shows the proportion of benefiting areas supported by spatial ecosystem service flows from provisioning areas. We illustrate the application of the framework and indicator by using global maps of provisioning and benefitting areas for pollination services. We also illustrate our framework and indicator using water provision and climate regulation services, as they portray important differences in spatiotemporal scale and process of service flow. We also describe the possible application of the framework for other services and other scales of assessment. We highlight how, depending on the ecosystem service being studied, the spatial service flows between provisioning and benefiting areas can limit service delivery, thereby reducing the local value of ecosystem service supply.

1. Introduction

Ecosystem services comprise 'the ecosystems conditions or processes utilized, actively or passively, to produce human well-being' (MA, 2005; Fisher et al., 2009). The strict coupling in the definition of ecosystem services to human utilization has important consequences. First, there is a considerable difference between 'potential' and 'actual' service provision, since ecosystem conditions and processes only become services once they are actually used or consumed by human beneficiaries (Fisher et al., 2009). Second, there may be spatial dissimilarities between areas where services are produced and where they are to be used. This implies that most ecosystem services are 'delivered' from provisioning to benefiting areas through either biophysical or anthropogenic processes. How the production connects with human beneficiaries is a crucial feature of the ecosystem service concept: the flow of services in space and time. To date, the use of the term 'ecosystem service flow' has been ambiguous, referring either to general service provision or to the path of delivery from providing to benefiting areas (*e.g.*, Chan et al., 2006; Fisher et al., 2011; Bagstad et al., 2013). We define ecosystem service flows as the spatial and temporal connections between provisioning and benefiting areas. This definition centers ecosystem service flows as means for actual service provision (*e.g.*, Reyers et al., 2010; Fisher et al., 2011; Turner et al., 2012) and, hence, complements the view of service provision to beneficiaries. Information on when and where benefits are enjoyed is required for designing and applying economic instruments, such as payments for ecosystem services (Wunder, 2007; Guariguata and Balvanera, 2009). For instance, the characterization of ecosystem service flows is crucial to identify key players in the efforts to mitigate climate change impacts through Reducing Emissions from Deforestation and Forest Degradation mechanisms (REDD+,

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Agrawal et al., 2011). Additionally, the study of ecosystem service flows could highlight constraints as well as options to restore the delivery of services to beneficiaries, which is a key target of Action 2 of the European Union's 2020 Biodiversity Strategy,[1] and a strategic goal in the Convention on Biological Diversity's 2020 targets ('enhancing benefits from ecosystem services', Perrings et al., 2010).

To date, studies on ecosystem service flows are sparse and rather conceptual (Silvestri and Kershaw, 2010; Bastian et al., 2012; Syrbe and Walz, 2012). The temporal features of ecosystem service flows have rarely been addressed (*e.g.*, Brauman et al., 2007; Bastian et al., 2012) and our understanding of the spatial features of service flows relies heavily on broad categories of the spatial relations between provisioning and benefiting areas (Costanza, 2008; Fisher et al., 2009). For instance, soil formation and erosion regulation are classified as *in situ* services, because providing and benefiting areas overlap completely. For storm and flood protection, service delivery depends on proximity (Brauman et al., 2007; Costanza, 2008; Fisher et al., 2009). For climate regulation, the delivery is global and omnidirectional (Costanza, 2008). Recently, Syrbe and Walz (2012) defined "the intervening space between non-contiguous providing and benefiting areas that influence process variables" as service connecting areas. This definition only indirectly addresses the spatial features of service flows and without quantification. This leaves a challenge quantifying the connections between ecosystems as service providers and the beneficiaries of those services.

Spatial assessments pairing provisioning areas with the corresponding benefiting areas can provide insights into the role of spatial flows in the delivery of a particular ecosystem service. Current mapping of ecosystem services has more often focused on the potential rather than the actual provision (*e.g.*, Chan et al., 2006; Kienast et al., 2009; Haines-Young et al., 2012). Owing to the misrepresentation of actual provision and benefits, and the use of different input data and methodologies, considerable differences in the extent of ecosystem service provision and benefits are found among studies (Eigenbrod et al., 2010; Holland et al., 2011). The inclusion of the demand side, *i.e.*, the corresponding benefit and beneficiaries, is yet to become an integral part of assessments (*e.g.*, Burkhard et al., 2012; Schulp et al., 2014). Only in a few regional-scale studies have the spatial features of ecosystem service flows been illustrated and estimated, *e.g.*, indirectly, by mapping 'supply and demand' (Fisher et al., 2011; Burkhard et al., 2012), and directly by, *e.g.*, estimating the perceived benefits from different forested areas to a given settlement (Palomo et al., 2012). At large scales the spatial connections between providing and benefiting areas for ecosystem services related to the trade in specific commodities, such as wood, fish and agricultural goods, have well been studied (Hoekstra and Hung, 2005; Deutsch et al., 2007; Kastner et al., 2011). The methodologies used to map and quantify the flow of such commodities, however, are only applicable for services that are marketable and tracked by international trade agencies.

A prominent study that explicitly used the spatial connections between providing and benefiting areas to evaluate spatial service flows is the one conducted by Turner et al. (2012). They examined how global ecosystem service values are realized and constructed spatial models of flow to estimate the population able to capture benefits. Their study makes an important step by explicitly modeling spatial flows to estimate the value of the delivered benefits. This approach, however, is difficult to extend and generalize to other applications given their agglomeration of individual spatial flows into coarse categories.

[1] http://ec.europa.eu/environment/nature/biodiversity/comm2006/2020.htm.

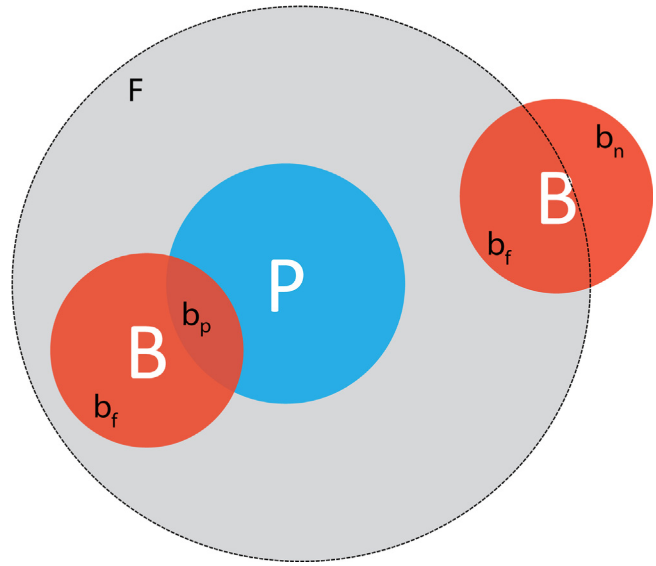

Fig. 1. Framework to analyze and quantify ecosystem service flows. Red circles with *B*, represent benefiting areas, while blue circle with *P* represents provisioning areas. *F* is the flow area within which services from provisioning area can potentially be delivered; b_f is the benefiting area not overlapping with *P* but within *F*; b_n is the benefiting area not-overlapping with the provisioning area and outside *F*; b_p is the benefiting area overlapping with the provisioning area.

In this article, we aim to assess the spatial flows of individual ecosystem services by mapping provisioning areas and the corresponding benefiting areas using a generic framework. Following this framework, we derive an indicator that characterizes the extent to which benefiting areas depend on spatial flows from other locations. We illustrate this approach by mapping, at the global scale, a number of illustrative ecosystem services that show distinctly different relations between provisioning and benefitting areas. Finally, we discuss how the framework can be applied in other settings to study the actual provision of ecosystem services.

2. Materials and methods

2.1. A generic framework to characterize and quantify spatial flows of ecosystem services

The framework we use to analyze the spatial relationships between ecosystem service providing and benefiting areas is illustrated in Fig. 1. The blue circle (*P*) represents a provisioning area, here defined as the spatial unit from which ecosystem services are sourced. The gray circle (*F*) represents the flow area, delineated by a maximum or threshold distance from the outer perimeter of the provisioning area (*P*) within which services can be 'delivered' to beneficiaries. Red circles (*B*) represent benefiting areas, defined as those spatial units in which ecosystem services are needed or readily used or consumed. The benefiting areas are further characterized as: *bp*, the benefiting area overlapping with the provisioning area; *bf*, benefiting areas *not* overlapping with the provisioning area but within the flow area (*F*); and *bn*, the benefiting area not overlapping with the provisioning area *and* outside the flow area (*F*). An indicator for the importance of spatial flows for benefits from ecosystem services (*Ben.flow*) can be calculated as the ratio between the proportion of benefiting areas located within the flow area (b_f) and the total benefiting areas:

$$\%Ben.flow = \left(\frac{b_f}{b_f + b_p}\right) \times 100$$