Service Path Attribution Networks (SPANs): Spatially Quantifying the Flow of Ecosystem Services from Landscapes to People

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Abstract. Ecosystem services are the effects on human well-being of the flow of benefits from ecosystems to people over given extents of space and time. The Service Path Attribution Network (SPAN) model provides a spatial framework for quantifying these flows, providing a new means of estimating these economic benefits. This approach discovers dependencies between provision and usage endpoints, spatial competition among users for scarce resources, and landscape effects on ecosystem service flows. Particularly novel is the model's ability to identify the relative density of these flows throughout landscapes and to determine which areas are affected by upstream flow depletion. SPAN descriptions have been developed for a number of services(aesthetic viewsheds, proximity to open space, carbon sequestration, flood mitigation, nutrient cycling, and avoided sedimentation/deposition), which vary in scale of effect, mechanism of provision and use, and type of flow. Results using real world data are shown for the US Puget Sound region.

Keywords: ecosystem services, ecosystem service assessment, SPAN model, service path attribution network, environmental planning, service flows, flow modeling, flow density, flow criticality.

1 Introduction

The concept of Ecosystem Services (ES) provides a cohesive scientific view of the many mechanisms through which nature contributes to human well-being[5]. Focusing on both the biophysical mechanisms of ES provision and the economic implications of ES use can allow our societies to balance the sides of the "nature vs. economy" equation, leading to better management and governance[10]. Natural systems provide valuable physical resources to support daily life, regulation of local through global processes within ranges appropriate for human survival, and cultural benefits that satisfy psychological, emotional, and cultural needs. These values, which can be determined by the careful application of ecological

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and economic principles, should be factored into decisions that influence the state of natural systems and the services they provide[5,11,10].

Understanding and modeling the complexities of coupled human-natural systems requires researchers to combine techniques from both socio-economics and the physical sciences. A major hurdle to this union is in overcoming the very different underlying assumptions, scales, and applications of the main modeling techniques used in these fields. Additionally, even with the best of intentions, many of the interactions between humans and their environments remain as of yet unknown[9].

For these reasons, concrete techniques for supporting quantification, spatial mapping and economic valuation of ES have lagged behind the popularity of the concept, making it difficult to productively use ES as a basis for scientific investigation and accurate decision-making [3,17]. Virtually all methodologies employed or proposed [4,6,12,15] to quantify ES and their values convert proxy categorical information, chiefly land cover type, into coarse assessments of value or potential provision through the use of aggregated coefficients. Such approaches ignore the complex, multi-scale dynamics of ES provision, use, and flow and are insufficiently precise to enable detailed scenario analyses or inform spatial planning decisions. Current approaches tend to address the following three points unsatisfactorily:

1. **Scalability:** Ecosystem services are provided and used at a wide variety of spatial and temporal scales[8,7]. However, most current spatial ES models are calibrated to operate on one fixed scale. A robust model would be able to adapt its scale and associated complexity to match each problem.
2. **Generalizability:** The algorithms used in the model analysis should be transparent enough for decision-makers in the field of ecosystem services to understand (and modify as necessary), while being robust enough to handle a variety of different services and applications.
3. **Benefit-Centrism:** Although earth system simulation modeling is a well established field, especially with respect to climate and hydrologic modeling, these models focus largely or exclusively on describing and predicting how physical environmental systems behave under varying conditions. The effects of the environmental system on the human economic system (and vice versa) must be central to the model, as assessing these is the heart of ecosystem service assessment and valuation[3,17,1].

This contribution addresses these issues through a combination of network analysis, dynamic programming, parallelism, and agent-based techniques. The end result is a model which emphasizes service *flows* rather than their in situ production, reflecting the definition of ecosystem services given in [16]: the effects on human well-being of the flow of benefits from an ecosystem endpoint to a human endpoint at given extents of space and time. This algorithm, called the Service Path Attribution Network (SPAN), discovers dependencies between provision and usage endpoints, spatial competition among users for scarce resources, and landscape effects on ecosystem service flows. Particularly novel is the model's ability to identify the relative density of these flows throughout landscapes and to determine which areas are affected by upstream flow depletion. SPAN descriptions have been developed for a number of services(aesthetic viewsheds, proximity to open space, carbon sequestration, flood mitigation, nutrient cycling, and avoided sedimentation/deposition), which vary in scale of effect, mechanism of provision and use, and type of flow. Due to page limitations, we concentrate on results obtained using real world data for the aesthetic viewshed service in the US Puget Sound region. Results for other services will be available online and in forthcoming publications[1].

2 Structure of the Model

In the SPAN model, both potential producers and beneficiaries of ecosystem services are spatially identified on the landscape, and the service flow from these ecosystems to their economic endpoints becomes the focus of the analysis. In this way, we can reach a more thorough understanding of which benefits are received by which people. We can also determine the degree to which landscape features and other human activities affect service flows and can use this information to suggest land management scenarios to decision makers that will increase or decrease these flows to meet their needs.

2.1 Mapping from Geospace to Vertices

A SPAN is implemented over a directed acyclic graph that represents the spatial relationships between those geographic areas that participate in the production, use, transport, or absorption of a given ecosystem service. Each spatial region is represented by a vertex in the graph, along with its underlying feature measurements. Each boundary element between adjacent regions is represented by a directed edge indicating the direction of service flow (see Figure 1).

Because the number of vertices in our network must be finite to perform this analysis, an initial step in building a SPAN is selecting the study scale and discretizing the overall region of interest into a set of spatially disjoint locations according to the particular service's production, use, and flow characteristics. Given the underlying georeferenced data set, this spatial segmentation process may be automated via techniques from image analysis, computer vision, or spatial data mining or may even be manually supplied using a predetermined partitioning, such as a map of geopolitical or bioregional boundaries.

Although many natural processes are often approximated by continuous models (e.g. hydrologic or atmospheric dynamics), we believe a discrete paradigm offers several advantages. First, environmental datasets are almost always comprised of discretely-sampled measurements. These usually come in the form of either polygon maps or regular grids with associated feature values at each measured location. Using discrete regions in the SPAN model allows us to match our algorithms to the same scale and representation as that of the underlying data. The second advantage is that agent-based algorithms can be readily applied to the data to identify

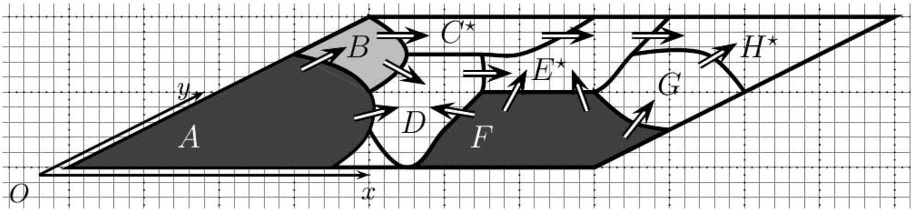

Fig. 1. Pixelated landscape segmented into regions by underlying feature measurements. Each region corresponds to a vertex in the SPAN, and the arrows depict the direction of service flow between regions. A and F are *source* regions, B is a service *sink*, and regions C, E, and H contain potential service *users*, denoted by an asterisk on the region's label.

flow pathways between service providers and beneficiaries. A third and final advantage is that the computational complexity of some models can be reduced by aggregating high resolution data within each region into simpler representations, such as probability distributions or functional approximations, which the agent system may then use as input. A caveat to this is that acceptable scales for downsampling must be fine enough to accurately represent the movement of the given service and are thus constrained by its flow properties.

2.2 Service Medium and Service Carriers

In order to simulate the flows of ecosystem services through the model, the analysis of a SPAN requires an additional component, called the *service medium*. This is the particular form of matter, energy, or information that transmits the chosen service between geospatial locations and therefore also through the SPAN to which they are mapped. Depending on the service, the medium's propagation may represent the movement of a benefit (like food, clean water, or scenic views) or a detriment (like the movement of excessive sediment, nutrients, or floodwater). We term the former services *provisioning services*, as the provision of the service medium by an ecosystem to a human beneficiary group represents a benefit.[1] We term the latter services *preventative services*, since the benefit is provided by an ecosystem's prevention of the service medium reaching a beneficiary. Thus for some ecosystem services, accumulation of the medium by beneficiaries provides economic value, while for other services, the value is accrued by preventing this accumulation.

In the network, the service medium is reified as a collection of service carrier agents, represented as pairs (W, R) with the following meaning:

- **Service Weight W:** A numeric (or otherwise quantifiable) representation of the quantity or quality of the service medium that a service carrier is transporting through the network.

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[1] This definition of the term *provisioning services* differs from that given in the Millenium Assessment, in which it is used to mean physical goods obtained from ecosystems.[10].

- **Service Route R:** A list of the vertices $(v_1, v_2, \ldots, v_N)$, through which this service carrier has traveled, inclusive of the vertex in which the carrier is currently located. The current vertex can be addressed as $\mathrm{Last}(R)$. Similarly the first vertex in the carrier's route may be accessed as $\mathrm{First}(R)$.

The movement of these carriers through the SPAN is then specified by three parameters:

1. **Movement Function,** $\mathrm{Move} : (W, R) \rightarrow ((W, R)*)$**:** This function maps a carrier (W_0, R_0) to a list of new carriers $((W_1, R_1), (W_2, R_2), \ldots, (W_N, R_N))$, where N is the number of outgoing edges from $\mathrm{Last}(R_0)$. These represent the next steps of the service carrier through the SPAN. Each new carrier route is formed by appending one of the vertices reachable by an outgoing edge from $\mathrm{Last}(R_0)$ onto R_0. All vertices directly reachable by an outgoing edge are represented without repetition. The weights associated with these routes describe the amount of service medium which follows each particular route away from $\mathrm{Last}(R_0)$. If a carrier moves into a vertex with no outgoing edges, then $\mathrm{Move}((W, R))$ evaluates to an empty list.
2. **Decay Function,** $\mathrm{Decay} : (W, R) \rightarrow W'$**:** Some service media may decay in quality or importance as a function of the distance they travel or by some limiting effect of the route they follow. For example, the view of a mountain becomes less impressive the further away it is. We represent this in the SPAN by a function that maps a service carrier to a new weight $W' \leq W$ which is the remaining weight after applying the decay effects along the route R. In order to reverse this calculation (as required by Section 3.3), a corresponding function $\mathrm{Undecay} : (W', R) \rightarrow W$ must also be supplied.
3. **Transition Threshold,** θ_{trans}**:** This is the minimum weight that any carrier in the network must have in order to be a candidate for the Movement function. Should a service carrier's weight W ever become less than θ_{trans}, then the carrier expires and the medium it bears ceases to propagate any further. Increasing this value will decrease the maximum route length for carriers.

2.3 Location Properties

With the study area partitioned and the service medium identified, each vertex v in the SPAN is assigned eight properties (see Table 1), which describe its region's effects on the service medium. Those properties labeled *Concrete* are expressed in physical units. Those labeled *Abstract* are represented with a unitless value from $[0, 1]$. The properties that saturate represent limited absorption or usage capacities. Regions with these values will not absorb or use quantities of the service medium greater than these limits during the flow analysis. Conversely, the non-saturating properties represent amounts of absorption or usage that are entirely dependent on the amount of the service medium encountered.

For many but not all ecosystem services, either the absolute or the relative forms of the source, sink, and use functions are defined. In general, cultural and aesthetic services (e.g. scenic viewsheds, proximity to open space, or preservation of a cultural icon) are most easily modeled using relative source, sink,

Table 1. Location properties assigned to each vertex in the SPAN

Location Property	Function	Unit Type	Saturating	Relationship to Medium
Absolute Source	$\mathrm{Source}_{\mathrm{abs}}(v)$	Concrete	N/A	Amount produced
Absolute Sink	$\mathrm{Sink}_{\mathrm{abs}}(v)$	Concrete	Yes	Amount potentially absorbed
Minimum Absolute Use	$\mathrm{Use}_{\mathrm{abs}}^{\mathrm{min}}(v)$	Concrete	Yes	Amount potentially unusable
Maximum Absolute Use	$\mathrm{Use}_{\mathrm{abs}}^{\mathrm{max}}(v)$	Concrete	Yes	Amount potentially usable
Relative Source	$\mathrm{Source}_{\mathrm{rel}}(v)$	Abstract	N/A	Amount produced
Relative Sink	$\mathrm{Sink}_{\mathrm{rel}}(v)$	Abstract	No	Percent potentially absorbed
Minimum Relative Use	$\mathrm{Use}_{\mathrm{rel}}^{\mathrm{min}}(v)$	Abstract	No	Percent potentially unusable
Maximum Relative Use	$\mathrm{Use}_{\mathrm{rel}}^{\mathrm{max}}(v)$	Abstract	No	Percent potentially usable

and use values. Concrete values are better suited to represent services based on the movement of matter or energy across landscapes (e.g. water provision, flood mitigation, or carbon sequestration). In this case, the absolute source value of a region represents the amount of the medium (i.e. runoff or carbon sequestration – including avoided release of stored carbon) that it produces during the simulation. Since the SPAN model currently operates statically in time, this source value is based on a predefined time window or a particular event, such as a 100-year storm.

Of particular interest are the minimum and maximum use values. For a provisioning service, a region's minimum use value denotes the amount of the service medium which cannot be used by the beneficiaries within its bounds, stated in either physical units or as a percentage of the total quantity encountered. Maximum use indicates the total that can be captured by beneficiaries. These may be used to represent both institutional constraints as well as physical or technological limitations on the extraction process. For a preventative service, the minimum use value should be interpreted as a limit on the amount of the service medium encountered which will not cause any measurable damage to the beneficiaries in a region. Maximum use then represents the amount beyond which no further damage is caused (because all assets of note have already been ruined).

A final property of service usage is that it may be either destructive or non-destructive on the service medium. This is correlated with the rivalness[2] of the resource being analyzed. For example, with water provision, the extraction and use of water is clearly rival and destructive of the resource since collecting it in one region prevents its use by all downstream regions. The same applies to carbon sequestration, as a finite quantity of carbon sequestration capacity must be shared among all users in order to maintain the atmospheric carbon

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[2] A rival good is one whose use or consumption by one party leaves less available for use or consumption by others[13]. Most physical goods and commodities bought and sold in the market are rival goods. A non-rival good is one that can be used by multiple parties without leaving less available for others. Examples include public safety, information in the public domain, and most regulating and cultural values provided by ecosystems.

balance at a safe level. However, in the case of flood mitigation, the same water that causes flood damage in one region may cause further damage in others. Thus, by providing the service of flood mitigation to one area, many areas may simultaneously receive the same benefit depending on their spatial configuration. The same non-rivalness may often hold for the informational or accessibility-based services. As an example, the availability of scenic viewsheds may benefit many users in different regions without competition for this resource.

2.4 Property Thresholds

As a means of restricting service flow calculations to parts of the system deemed more important than others, a positive, real-valued threshold may be associated with each of the above location properties. These shall be labeled as follows:

$$\theta_t^m, \quad \text{where, } m \in \{\text{abs}, \text{rel}\}, t \in \{\text{source}, \text{sink}, \text{use}\}.$$

These thresholds will be used to determine the vertex sets S, K, and U in the following section.

2.5 The Graph Specification

Now that the mapping from geospace to vertices has been detailed and all the necessary terminology introduced, we can present the graph specification of our SPAN model in detail. A SPAN is built on a directed graph $G = (V, E)$, possessing the following six properties:

1. Every vertex $v \in V$ represents a single geospatial area, whose polygon-bounded region is distinct and does not overlap topologically with that of any other vertex $v' \in V$.
2. Every directed edge $(u, v) \in E$ represents a path along which a service carrier may travel from location u to location v. This path may represent an adjacency relationship (shared boundary) between u and v in the georeferenced space, but it may also connect two spatially separated locations in the event that the service medium's flow may be better modeled in such a manner. For example, two cities which are accessible along the same train line may be connected by an edge in the SPAN for services which may travel along human transportation networks.
3. A subset $S \subseteq V$ contains those vertices which we shall call *service sources*. For each $s \in S$, either $\text{Source}_{\text{abs}}(s) \geq \theta_{\text{source}}^{\text{abs}}$ or $\text{Source}_{\text{rel}}(s) \geq \theta_{\text{source}}^{\text{rel}}$, depending on whether the source is absolute or relative.
4. A subset $K \subseteq V$ contains those vertices which we shall call *service sinks*. For each $k \in K$, $\text{Sink}_{\text{abs}}(k) \geq \theta_{\text{sink}}^{\text{abs}}$ or $\text{Sink}_{\text{rel}}(k) \geq \theta_{\text{sink}}^{\text{rel}}$, depending on whether the sink is absolute or relative.
5. A subset $U \subseteq V$ contains those vertices which we shall call *service users*. For each $u \in U$, $\text{Use}_{\text{abs}}^{\max}(u) \geq \theta_{\text{use}}^{\text{abs}}$ or $\text{Use}_{\text{rel}}^{\max}(u) \geq \theta_{\text{use}}^{\text{rel}}$, depending on whether the use is absolute or relative.
6. S, K, and U need not be disjoint.

This completes the description of the SPAN model's structure, parametrization, and correspondence to the underlying spatial data. Next, we must connect the regions providing services with their beneficiaries.

3 Flow Analysis

Thus far, the ecosystem service properties of our study area have been determined within each region without regard to the relationships between regions. We call these values the *theoretical* source, sink, and use estimates of our service assessment because without determining where the service medium generated at the sources will flow, we cannot determine who, if anyone, will receive its benefits or which sinks will actually impede its movement. This highlights an important aspect of the SPAN model's definition of service provision: unless the generated benefit is actually made accessible to human beneficiaries, no service is attributed to the ecosystem. Furthermore, since services can flow to beneficiaries from different sources, it is important to correctly assign value to sources that are actually used.

The algorithm that determines these spatial relationships consists of four phases: Discovering the Flow Topology, Sorting Routes by Dependence, Applying Sink and Rival Use Effects, and Analyzing the Carrier Paths.

3.1 Discovering the Flow Topology

First, each vertex v in the graph is assigned two empty sets, which we shall call its *carrier caches*, $\mathrm{Cache}_{\mathrm{possible}}(v)$ and $\mathrm{Cache}_{\mathrm{actual}}(v)$. A service carrier is initialized in each source vertex $s \in S$ with its weight and route (W, R) set as either $(\mathrm{Source}_{\mathrm{abs}}(s), (s))$ or $(\mathrm{Source}_{\mathrm{rel}}(s), (s))$, depending on the service medium. Each carrier is then used as the root node of a depth-first tree traversal in which $\mathrm{Move}((W, R))$ is used as the successor function at each step. During this phase of the traversal, the weight values of the carriers are only reduced by path branching (i.e. when a parent's weight is divided among multiple children) or distance decay as computed by the $\mathrm{Decay}((W, R))$ function. The leaf nodes on this carrier graph are both those for which $\mathrm{Move}((W, R))$ returns no children as well as those for which $\mathrm{Decay}((W, R)) < \theta_{\mathrm{trans}}$. Whenever a carrier (W, R) is created for which $\mathrm{Last}(R) \in K \cup U$, a new carrier $(\mathrm{Decay}((W, R)), R)$ is appended to $\mathrm{Cache}_{\mathrm{possible}}(\mathrm{Last}(R))$.

3.2 Sorting Routes by Dependence

Let $\mathrm{Carriers}_{\mathrm{unsorted}} = \bigcup_{v \in V} \mathrm{Cache}_{\mathrm{possible}}(v)$. Let $\mathrm{Carriers}_{\mathrm{sorted}}$ be a list containing all the members of $\mathrm{Carriers}_{\mathrm{unsorted}}$ ordered according to the following constraint: Given a carrier (W, R) in $\mathrm{Carriers}_{\mathrm{unsorted}}$, select the last vertex r in R that belongs to K, or that belongs to $K \cup U$ if the service is rival, excluding $\mathrm{Last}(R)$. All carriers in $\mathrm{Cache}_{\mathrm{possible}}(r)$ must appear before (W, R) in $\mathrm{Carriers}_{\mathrm{sorted}}$.

3.3 Applying Sink and Rival Use Effects

Next, we want to determine the degree to which landscape sinks and human users along the flow paths deplete the service carrier weights which they encounter. We first establish the following definitions:

$$\mathrm{Input}_{\mathrm{actual}}(v) = \begin{cases} \displaystyle\sum_{(W,R)\in \mathrm{Cache}_{\mathrm{actual}}(v)} W, & \text{if } |\mathrm{Cache}_{\mathrm{actual}}(v)| > 0 \\ 1, & \text{otherwise} \end{cases}$$

$$W_{\mathrm{contrib}}(w,v) = \frac{w}{\mathrm{Input}_{\mathrm{actual}}(v)}$$

$$W_{\mathrm{sink}}(w,v) = \begin{cases} w \times \mathrm{Sink}_{\mathrm{rel}}(v), & \text{if } \mathrm{Sink}_{\mathrm{rel}}(v) > 0 \\ W_{\mathrm{contrib}}(w,v) \times \\ \quad \min\left(\mathrm{Input}_{\mathrm{actual}}(v), \mathrm{Sink}_{\mathrm{abs}}(v)\right), & \text{otherwise} \end{cases}$$

$$W_{\mathrm{unusable}}(w,v) = \begin{cases} w \times \mathrm{Use}^{\mathrm{min}}_{\mathrm{rel}}(v), & \text{if } \mathrm{Use}^{\mathrm{min}}_{\mathrm{rel}}(v) > 0 \\ \min\left(w, W_{\mathrm{contrib}}(w,v) \times \mathrm{Use}^{\mathrm{min}}_{\mathrm{abs}}(v)\right), & \text{otherwise} \end{cases}$$

$$W_{\mathrm{used}}(w,v) = \begin{cases} (w - W_{\mathrm{unusable}}(w,v)) \times \mathrm{Use}^{\mathrm{max}}_{\mathrm{rel}}(v), & \text{if } \mathrm{Use}^{\mathrm{max}}_{\mathrm{rel}}(v) > 0 \\ \min\left(w - W_{\mathrm{unusable}}(w,v),\right. \\ \quad \left. W_{\mathrm{contrib}}(w,v) \times \mathrm{Use}^{\mathrm{max}}_{\mathrm{abs}}(v)\right) & \text{otherwise} \end{cases}$$

Select the first carrier (W, R) in $\mathrm{Carriers}_{\mathrm{sorted}}$ and retrace its route, allowing the sink and use regions along it, if any, to reduce its service weight as follows:

Compute the route's undecayed weight value $\mathrm{Undecay}((W, R))$. Initialize w to this value, and let it represent the remaining weight after each successive reduction. Let v assume the values sequentially between $\mathrm{First}(R)$ and $\mathrm{Last}(R)$. Whenever $v \in K$, subtract $W_{\mathrm{sink}}(w, v)$ from the weight remaining and call this w. If the service is rival and $v \in U$, subtract $W_{\mathrm{used}}(w, v)$ from the post-sunk weight. Finally, apply Decay to w at this step, and if it is greater than θ_{trans}, continue to the next value of v.

After all sink and use effects along route R have been applied, append a new carrier (w, R) to $\mathrm{Cache}_{\mathrm{actual}}(\mathrm{Last}(R))$. Repeat this algorithm for each successive carrier in $\mathrm{Carriers}_{\mathrm{sorted}}$. By generating these carriers in the order determined by the path sorting phase, each $\mathrm{Cache}_{\mathrm{actual}}(v)$ will be fully populated before any $W_{\mathrm{sink}}(w, v)$ or $W_{\mathrm{used}}(w, v)$ calculations that depend on it will be performed.

At this point, for all $v \in V$, $\mathrm{Cache}_{\mathrm{possible}}(v)$ has been populated with service carriers (W, R) which indicate the amount of benefit W that could be transmitted along route R if the effects of sinks and rival uses were nullified. For each such carrier (W, R) in $\mathrm{Cache}_{\mathrm{possible}}(v)$, $\mathrm{Cache}_{\mathrm{actual}}(v)$ contains a corresponding carrier

(w, R), which denotes the amount of benefit w expected to travel along R when the effects of sinks and rival uses are factored in.

3.4 Analyzing the Carrier Paths

Once the flow model has completed execution, the two carrier caches are analyzed to determine the total amount of service each location receives from each producer, which sinks and rival use effects block downstream access to the service medium, and what parts of the landscape exhibit the greatest flow density. All of these calculations are possible because the weighted routes stored during the simulation record spatial information about each of these effects on the flow.

The results of this path analysis are several:

1. **Theoretical Source, Sink, Use:** The names given to the in situ location properties of each site determined prior to flow analysis as described in Section 2.3. These are included for completeness and comparison.
2. **Possible Source, Sink, Use, Flow:** Source amounts reachable by users along flow paths determined by landscape topology and topography and the medium's flow characteristics, estimates of sink absorption and usage capacity actualized along these flow paths as functions of the quantity of the medium encountered, and flow density through each region in the study area. All values are calculated by disregarding the effects of sink and rival use locations upstream of each region. This provides an upper bound for the landscape's service flow potential if development scenarios are implemented which minimize these effects.
3. **Actual Source, Sink, Use, Flow:** Same as the Possible values, except that sink and rival use effects are included in their calculation. This provides a snapshot of the actual state of ecosystem service flows in the region.
4. **Inaccessible Source, Sink, Use:** The difference between Theoretical and Possible values. Unreachable source production, unutilized sinks, and unsaturated use capacity due to flow topology.
5. **Blocked Source, Sink, Use, Flow:** The difference between Possible and Actual values. Unreachable source production, unutilized sinks, and unsaturated user capacity due to sink and rival use effects.

For provisioning services, the use values calculated in this stage represent met (or unmet) user demand, sinks are considered detrimental, and source regions are valued according to the amount of service they produce which is received by human beneficiaries. Because receipt of the service medium is desirable, the landscape features which facilitate its transport through intermediate regions are also of value.

For preventative services, greater use indicates greater damage incurred due to encounters with the service medium. Regions with high source estimates or flow densities are undesirable, and sinks along flow paths become the providers of value to human beneficiaries. This approach can be used to quantify the effectiveness of landscape features in mitigating or blocking flow propagated threats, such as flood waters, wildfires, or mudslides.

This information, in combination with maps of the flow topology and density, can be used to target spatial planning decisions that intend to change or preserve service flows as well as to identify the comparative effects on ecosystem services of different development actions before they are enacted.

4 Results

The SPAN model described above has been implemented as a core component of the NSF-funded "ARtificial Intelligence for Ecosystem Services"(ARIES) project's software infrastructure. In this context, spatial environmental and economic datasets for model calibration and testing have been made available by case study partners in the Puget Sound[3] and Madagascar[4]. Discretization of the landscape was performed by converting all geographic data to a common resolution pixel-grid (raster) format. The location properties (see Table 2.3) were described using Bayesian networks, which were initially designed based on literature reviews and were later vetted and extended by local experts in each case study area (see Acknowledgements). Move and Decay functions, θ_{trans}, and the property thresholds were also provided by experts associated with each project for each service under study.

4.1 Aesthetic Viewsheds

As a first example, we examine benefits provided by unimpeded views of natural landscapes (e.g. the economic value of views of mountains and water bodies as measured using hedonic analysis[2]). In this case, the service medium is a measure of "scenic beauty" that is propagated by a movement function which follows lines of sight to potential beneficiaries. $\text{Source}_{\text{rel}}(v)$ assigns each grid cell v a qualitative beauty measure with respect to all other cells in the study area. $\text{Use}_{\text{rel}}^{\max}(v)$ highlights potential users of this service (for example, property owners in a given development district). Finally, $\text{Sink}_{\text{rel}}(v)$ depicts the presence of landscape features whose presence along a line of sight may detract from the view quality (i.e. billboards, clearcuts, industrial development). $\text{Decay}(W, R) = W/4\pi|R|^2$ so that the impact of a view drops off quadratically with distance, and θ_{trans} is set arbitrarily small enough to allow carrier propagation across the entire study area. Optionally, increasing θ_{trans} restricts smaller carriers from transmitting service and can be used as a filter for discovering which areas receive the most service from each provision region.

In the following diagrams, the pre- and post-flow estimates of the source, sink, use and flow density values are shown for the landscape surrounding the city of Kent, WA in the US Puget Sound region. Note, in particular, that the possible source which is available to beneficiaries in Kent is much less (denoted by its lighter shading) than the theoretical source due to the visually detracting effects of commercial and industrial development around the city.

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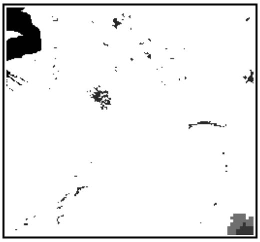
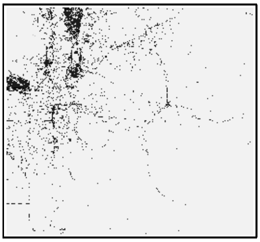
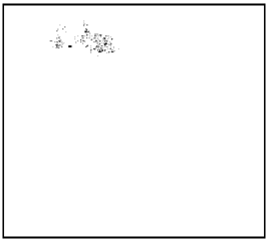
[3] Earth Economics: http://eartheconomics.org

[4] Conservation International: http://www.conservation.org


Theoretical View Source


Theoretical View Sink


Theoretical View Use

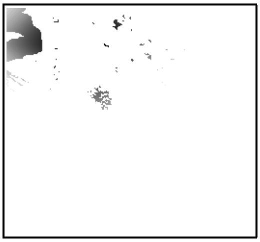
The dark area in the upper left of the first image is part of the Puget Sound and that in the lower right is the portion of Mount Rainier within the study area. These and the smaller water bodies and hills scattered across the map are detected as sources of scenic beauty by the $\text{Source}_{\text{rel}}$ function. The second image shows potential sink zones (here denoted by commercial, industrial, and transportation-related development). The final image depicts the potential beneficiaries of the aesthetic view service: residential properties within the city of Kent.

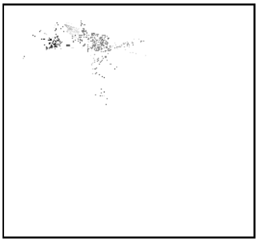

Possible View Flow

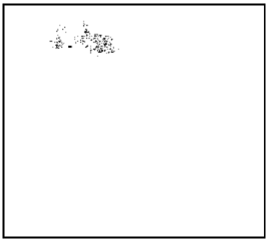

Blocked View Flow


Actual View Flow

These three maps indicate the flow densities between provision and use regions. The darkness of each path indicates the usable quality of the scenic beauty as it radiates from its point of origin toward the properties in Kent. The first shows all possible lines of sight along which the service medium may travel. The second depicts those flows which are blocked due to landscape sinks (i.e. obstructions and visual blight). The last shows the actual view quality when sink effects are taken into account.


Possible View Source


Possible View Sink


Possible View Use

In contrast with the theoretical (pre-flow) projections, the possible (post-flow) source and sink values are significantly lower across the study area, demonstrating the utility of flow information in filtering out those regions which do, in fact, participate in the transfer of benefits. The first image shows the degree to which each source region is actually visible from the properties within Kent due to the landscape's topography. The possible sink image identifies the subset of the theoretical sink regions which are actually in the view path between any source and use location. Should improved views be desired, this result identifies those areas wherein reduction of the sink strengths will be most effective. The final map shows the relative view quality at each use location. Its similarity to the theoretical use map indicates that most, if not all, of the use regions do have sight paths to some of the aesthetically beautiful source regions. However, since sink effects on flow quality are not taken into account in these maps, the reader should be aware that the substantial amount of visual blight will have a significant impact on reducing these values in the actual source, sink, and use maps.

5 Discussion

We have described in this paper the structure and operation of the SPAN model for quantitative ecosystem service assessment and have provided a sample of the kinds of novel results calculable using this approach. By adopting a discrete representation of the landscape as a collection of source, sink, and use regions which map to an abstract flow network, this framework can draw on a wide range of data aggregation techniques to match the scale of the assessment to the flow characteristics of the service being studied. Its benefit-centric focus on measuring flows of services from ecosystems to human beneficiaries enables more accurate value estimates than environmental simulations alone can provide. The provision and usage relationships between specific regions are clearly identified as well as the detrimental effects on service flows of both landscape features and human consumption. In instances in which different beneficiary groups compete for a finite resource, the flow paths clarify which groups have the earliest and/or easiest access. In cases of preventative services, the SPAN's multi-stage flow calculations make it possible to identify exactly how much flow (which represents potential threats) each sink region blocks from reaching each use region. Finally and perhaps most interestingly, discovering and mapping the flow densities for particular services opens the door to an entirely new approach to managing landscapes for ecosystem services. Rather than planning just to protect ecosystems which appear to provide services, ES science can begin to support more holistic development or conservation plans that account for both the service providers and the flow corridors crucial to the transmission of these benefits to human users.

5.1 Generalizability of the Model

Having addressed both the model's potential for scalability and the class of new results provided by its flow-based, benefit-centric approach to ecosystem services, the last element to discuss is its generalizability across services. Due to page limitations, only one service was described in detail in Section 4. To provide a wider range of examples, the following table maps a number of ecosystem services into the SPAN formalism. Although only a subset of the commonly described services[10], we believe these are sufficiently representative of the larger list as to enable the creation of mappings for other services. The examples shown vary in the type of benefit provided (provisioning or preventative), rivalness of the resource, units of representation (concrete or abstract), scale of effect, and movement function.

Service	**Aesthetic Viewsheds**	**Proximity to Open Space**
Benefit Type	Provisioning	Provisioning
Medium	Scenic Beauty	Open Space
Units	Abstract	Abstract
Scale	Viewshed	Walking Distance
Movement	Line of Sight (Ray Casting)	Walking Simulation
Decay	Inverse Square	Gaussian
Rival?	No	No
Source	Mountains & Water Bodies	Open Spaces in Urban Areas
Sink	Visual Blight	Walking Obstructions (Highways & Fences)
Min Use	0	0
Max Use	Property Value	Property Value
Service	**Carbon Sequestration**	**Flood Mitigation**
Benefit Type	Provisioning	Preventative
Medium	CO_2 Absorption	Water (Runoff)
Units	Concrete	Concrete
Scale	Global	Watershed
Movement	Atmospheric Mixing	Hydrologic Flow
Decay	None	None
Rival?	Yes	No
Source	Sequestration & Storage Capacity	Rainfall & Snowmelt
Sink	0	Water Absorption by Soil and Vegetation
Min Use	0	Minimum Water for Flood Damage
Max Use	Carbon Emissions	Minimum Water for Total Damage
Service	**Nutrient Cycling**	**Avoided Sedimentation/Deposition**
Benefit Type	Provisioning	Preventative
Medium	Nutrients in Water	Sediment
Units	Concrete	Concrete
Scale	Watershed	Watershed
Movement	Hydrologic Flow	Hydrologic Flow
Decay	None	None
Rival?	Yes	No
Source	Landscapes along Waterways	Landscapes along Waterways
Sink	Filters in Waterways	Riparian Zones
Min Use	Determined by Nutrient	Determined by Beneficiary
Max Use	Determined by Nutrient	Determined by Beneficiary

5.2 Open Problems and Next Steps

To conclude, we provide a short list of problems still to be addressed in order to improve the SPAN model's scalability, generalizability, and applicability to decision processes as well as to continue extending the frontiers in quantitative ecosystem service assessment.

First, upper limits on downsampling spatial datasets must be determined for each service flow type, below which total reconstruction of the flow path can be accurately determined. This problem is related to the Nyquist-Shannon sampling theorem and the aliasing problem[14]. Second, extending the SPAN formalism to operate over graphs with cycles will enable the assessment of new services such as those related with tidal or marine systems. Third, making movement functions and location property calculations non-deterministic will allow the modeling of unpredictable service media such as storms or wildfires. Fourth, investigating flow path substitutability will add further detail to maps of critical flow regions by making irreplaceable flow corridors more valuable than others.

Finally, the SPAN model can be used as a basis for spatial optimization techniques concerned with finding landscape configurations which maximize ES flow given cost (or other) constraints on spatial development activities.

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