ARIES (ARtificial Intelligence for Ecosystem Services): a new tool for ecosystem services assessment, planning, and valuation.

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ARIES is a new methodology and web application meant to assess ecosystem services (ES) and illuminate their values to humans in order to make environmental decisions easier and more effective. By creating ad-hoc, probabilistic models of both provision and usage of ES in a region of interest, and mapping the actual physical flows of those benefits to their beneficiaries, ARIES helps discover, understand, and quantify environmental assets, and what factors influence their value according to explicit needs and priorities. In this contribution, we present the basic elements of the ARIES methodology and illustrate perspectives for integration of new ES thinking into science, decision- and policy-making.

Introduction

The notion of Ecosystem Services (ES: (Daily 1997; Carpenter 2003; Kremen and Ostfeld 2005) provides a cohesive scientific view of the many mechanisms through which nature contributes to human well-being. 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. the economy” equation, leading to better management and governance (Millennium Ecosystem Assessment 2002). Unfortunately, the quantitative understanding to support quantification, spatial mapping and economic valuation of ES has lagged behind the popularity of the notion, making it difficult to productively use ES as a base for scientific investigation and accurate decision- and policy-making (Fisher, Turner et al. 2006; Boyd and Banzhaf 2007; Wallace 2007). Virtually all methods employed or proposed (Costanza, dArge et al. 1997; Wilson and Carpenter 1999; Farber, Costanza et al. 2006; Nelson, Mendoza et al. 2009; Tallis and Polasky 2009) 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 do not offer enough accuracy to inform decision and allow for scenario analysis in a quantitative and spatially explicit fashion.

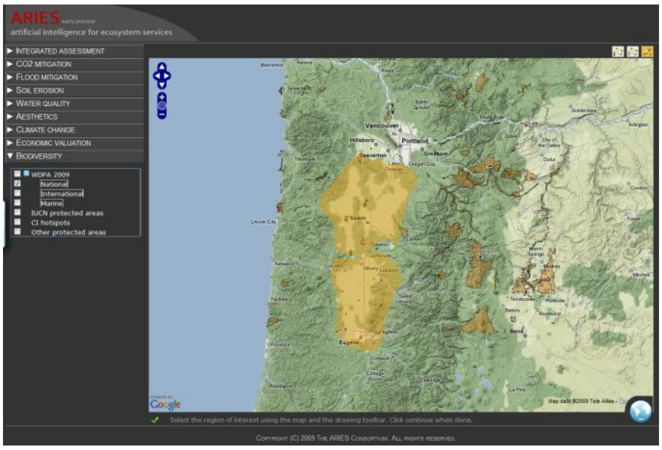


Figure 1. A screen capture from the preliminary ARIES web interface. The yellow outlines have been drawn by the user to delimit the region of interest. Modules on the left can be activated to produce assessments of the corresponding services. Results such as those of Table 1 appear in the map.

This article describes the ARIES methodology (ARtificial Intelligence for Ecosystem Services), an application of advanced ecoinformatics to support a more accurate, science-based ES analysis while at the same time reducing its complexity and cost for the user. As detailed later, ARIES is a web-accessible application (Figure 1) that builds and runs ad-hoc models of ecosystem services provision, use and spatial flow in a given area based on a user-dependent set of goals. The methodology, incorporated into a web-based, rapid assessment software toolkit that is being fine-tuned in case studies in Madagascar, Puget Sound and Mexico, is generating pilot applications in sectors as diverse as conservation, governments from the municipal to the national level, and the oil, gas and mining industry (Waage, Stewart et al. 2008).

The quantitative inadequacy of the current ES notion

The modern notion of ecosystem services can be traced back to at least the early 1970s. Since the late 1990s, however, several well-known studies have codified ecosystem services into generally accepted lists or typologies (Daily 1997; DeGroot, Wilson et al. 2002) The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2002; Mooney, Cropper et al. 2004; Pereira, Queiroz et al. 2005) classified ecosystem services into “supporting services,” the ecological processes and functions that generate other ecosystem services, “regulating services” that maintain global and local conditions at levels appropriate for human survival, “provisioning services” that offer physical resources directly contributing to human well-being, and “cultural services” that satisfy psychological, emotional, and cultural needs. This classification has been extremely useful for communicating nature’s importance in satisfying different domains of human well-being. Yet recent authors have noted that the MA ecosystem services classification does not lend itself well to economic decision-making (Hein and van Ierland 2006; Boyd and Banzhaf 2007; Wallace 2007). This is because the MA categories do not explicitly link specific benefits to specific human beneficiaries of ecosystem services. Improved definition of these benefits and beneficiaries, combined with their spatial mapping, could aid in ecosystem service valuation, environmental accounting (Boyd and Banzhaf 2007), identification of winners and losers in conservation and development choices, and in supporting payments for ecosystem services programs.

From a spatial perspective, the supply side of ecosystem services has been relatively well-explored. A number of recent studies have used GIS analysis to measure the ecological factors contributing to the provision of certain services (Naidoo and Ricketts 2006; Beier, Patterson et al. 2008; Nelson, Mendoza et al. 2009). These studies explore how the provision of ecosystem services varies across the landscape. However, far fewer studies have explicitly identified the demand side, or human beneficiaries (Hein et al. 2006) or mapped these beneficiaries (Beier et al. 2008). Yet the need for such mapping is becoming increasingly recognized (Naidoo, Balmford et al. 2008). Supply and demand side mapping are complex, since ecosystem services provision and use often occur across different spatial and temporal scales (Hein et al. 2006). Others (Tallis and Polasky 2009) clearly describe the “spatial flow problem” in ecosystem services. The ecosystem services research community has as yet been unable to move beyond “static maps” to consider the cross-scale flows of ecosystem service to different groups of human beneficiaries. Existing attempts to categorization (Costanza 2008) break ecosystem services into coarse categories based on how their benefits spatially flow to beneficiaries but stop short of providing a quantitative conceptualization. In order to promote a breakthrough in ecosystem services assessment, we must start from the concepts of the MA framework, incorporate several key elements proposed by others, and move towards a science of ecosystem services that quantitatively assesses spatio-temporal flows of clearly identified benefits towards clearly identified beneficiaries.

Reconceptualizing ES: the ARIES approach

Most of the many difficulties of modelling ES depend on the high heterogeneity of behavior exhibited by the benefits they produce. Among these:

1. Provision and usage happen at entirely independent scales in space and time. Therefore, a scale-explicit approach needs to be taken, and theoretical instruments that can tackle multi-scale systems are lacking.
2. The "currency" of benefit provision is rarely an easily modelled biophysical quantity. Easier cases include, e.g., CO2: quantification of its exchange from vegetation to atmosphere may be all that's needed to assess benefits of carbon sequestration. Things are much more complex with currencies like sense of identity or avoided risk of flooding.
3. Little clarity exists in the literature about quantifiable definition of ES, their benefits, and the modalities of their propagation from ecosystem to human beneficiary.

The ARIES methodology is based on explicit conceptualizations (ontologies: Villa, Athanasiadis et al. 2009) that lay out first of all a novel vision of ES, based on the breakdown into individual benefits, each of which is modeled independently, then linked to the others. Domain ontologies in ARIES result from a large-scale expert consensus. Artificial intelligence techniques (machine reasoning, pattern recognition) examine source data and extract from the ontologies models that best represent the situation at hand. ARIES builds ad-hoc, probabilistic Bayesian Network models (Cowell, Dawid et al. 1999) that are used to map the ecological and socioeconomic factors contributing to the provision and use of ecosystem services. These models enable the use of corresponding GIS data to produce maps of ecosystem service provision and use. Spatial flow models are then used to identify the strengths of ecosystem service flows that provide benefits from ecosystems to people (Figure 2).

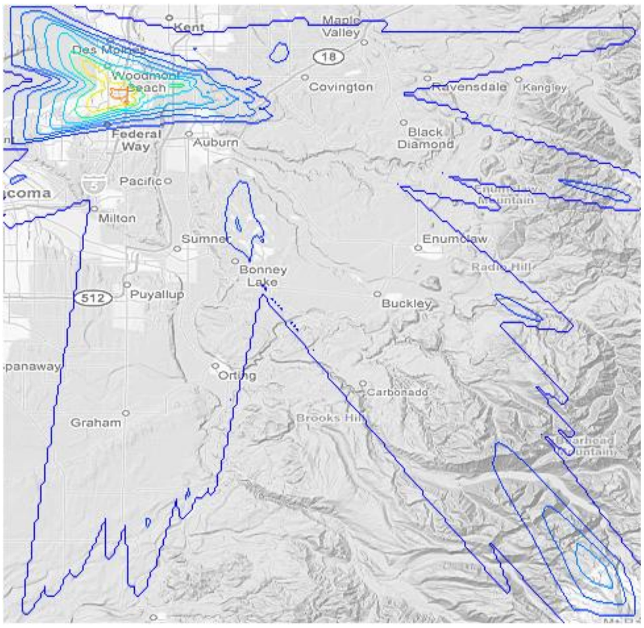


Figure 2. An example of the many novel results offered by ARIES: ecosystem service flow density plots allow informed siting decisions by showing areas that are critical to the flow of ES from point of provision to beneficiaries. The example refers to aesthetic value of Puget Sound view for the municipality of Kent. See later for details.

Identifying and mapping beneficiaries has been a key step in development of the ARIES methods. We have systematically defined ecosystem services and their provision and use processes using ontologies. Ontologies are designed to create common, mathematically formalized language for abstract concepts and relationships, promoting consistent, precise, and standardized understanding in these fields (Gruber 1995; Madin, Bowers et al. 2007). Within ARIES, ontologies also provide the knowledge base for a reasoning algorithm to extract models that are applied to data to quantify how ecosystem services are provided and used. More specifically, ontologies in ARIES specify:

1. A core vocabulary for ecosystem services, defining and classifying the general modalities of provision and use so that specific vocabularies can be built for specific services;
2. For each ecosystem service, the breakdown of specific, quantifiable, and spatially mappable benefits that the service produces, the corresponding classes of beneficiaries for each one, and the nature of the matter, energy or information that carries the benefit over space and promotes its transfer to humans (e.g. CO2, floodwater, or aesthetic information).
3. For each benefit, the set of components of both the natural and human system that need to be observed in order to characterize provision and use, so that an appropriately annotated database can be consulted to assess availability of experimental data for modelling.

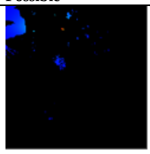
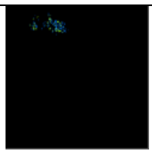
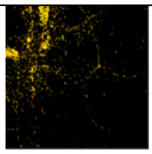
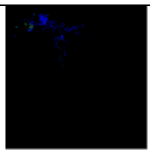
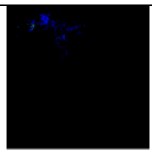
Following the consensus points described above, we identify the specific benefits and beneficiaries that flow from the typical MA ecosystem services categories. We also identify the spatial data layers needed to map the location of these beneficiaries. In order to enable the ARIES modelling paradigm, all benefits must meet five requirements. Specifically, benefits must be: 1) quantifiable, 2) directly valuable to humans, 3) provided by one clearly identified natural entity or process, 4) used by one clearly identified human consumer, and 5) provided through the transfer of a clearly identified carrier substance that can be material, energetic or informational (e.g. CO2 or floodwater). While we are primarily concerned with benefits and beneficiaries, we note that benefits are derived from ecosystem processes and structure. Ecosystem processes are analogous to "intermediate services," while the concept of final services can enable valuation of these final services or benefits. Once the full causal chain of provision and use is clearly identified, there is no need to distinguish "supporting services" or worry about double counting in valuation, because the base for valuation is the quantification of the actual flow of benefits and not of one of the processes that brings them into existence.

Methods

In ARIES, Ecosystem Services are *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*. The methodology combines spatially explicit models of ecosystem service provision and use with dynamic flow models to describe the distribution of benefits across the landscape. The exact form of these models depends on the specific context of application and is chosen by means of machine reasoning, on the basis of data analysis and ontological connotations of the services (e.g. the rival or non-rival nature of the benefits for their human beneficiaries, or the "protective" or "provisioning" character of the services). Because explicit uncertainty is crucial in decision-making, ARIES employs probabilistic models (spatial Bayesian networks) for all assessments, and joins models of provision, use and absorption of each benefit into a dynamic flow analysis that identifies the spatial pathways of provision of each ES from point of provision to point of use. Users can modify variables of interest (either under policy control, such as elevation or land cover, or external such as annual mean temperature or rainfall) and study their comparative effects.

The analytical steps in an ARIES session can be summarized as follows. In **Step 1,** benefits and beneficiaries of interest are determined by reasoning on the ARIES ontologies to choose the focal set of benefits, beneficiaries and the related information pertaining to the chosen context. The area of interest is drawn on a web-enabled interface (Figure 2) (UVM Ecoinformatics Collaboratory 2009) or uploaded by the user from a GIS file; the goals of the analysis (e.g. conservation planning or siting for planned development) are chosen by selecting a particularly "entry point" into the ARIES toolkit. From this input, ARIES

Table 1. A few of the 32 result maps that result from the ARIES assessment of a single benefit. The example refers to aesthetic view-shed analysis in the Puget Sound, one of the benefits associated with the ES “aesthetic and cultural values”. Source maps express the likelihood of providing aesthetic beauty (source) mostly from water bodies and mountains. Use maps express the likelihood of homeowners to be affected by aesthetic values and are based on population and property value data; sink maps express the likely detrimental effect of visual blight such as highways, strip malls etc. The flow model is a ray-cast algorithm calibrated to literature data for distance dampening factors; users can modify defaults of transparency to compare values in foggy or clear days. Users can select the amount of uncertainty they are willing to accept in the probabilistic models, and run the analysis only where uncertainty is lower.

Map type	**Theoretical**	**Possible**	**Blocked**	**Description**	**Practical uses**
SOURCE				ARIES maps ecosystems capable of supplying a benefit of interest and the amount of benefit potentially provided. **Theoretical provision** is the maximal amount deliverable independent of flow. **Possible** provision is the maximal amount that can flow to beneficiaries if sinks were not present. **Blocked** source is the service that cannot reach beneficiaries because it is absorbed by sinks. **Actual** provision is calculated as (Possible – Blocked).	Location of all actual and potential providers of an ES; quantification of the potential, actual and wasted amount of ES considering the intended beneficiaries. All other existing ES assessment methods only quantify theoretical provision.
USE				Beneficiaries capable of demanding a benefit of interest and amount of need for the benefit. Categories are similar to the ones for source values. Each ES typically has many different use categories. ARIES can tailor the analysis to each category and clearly identify the conflicts and distribution issues based on modeling of competing beneficiaries. It is common to model several beneficiaries per service in one ES assessment.	Location of all actual and potential human beneficiaries. E.g. Blocked use is a quantification of the unmet needs of a constituency; scenario analysis can be used to improve service delivery.
SINK				Sinks intercept and deplete benefit flows along their path from source to beneficiary. In *provisioning* services (such as the provisioning of water or fish) sinks decrease flow, e.g. by preventing access to resources: in *preventive* services, such as flood protection, sinks increase flow, e.g. by absorbing or routing floodwater. In *rival* benefits, users also act as sinks because they deplete the service, which is not an issue in *non-rival* services such as aesthetics.	Location of all actual and potential sinks. Often the location and strength of sinks is easier for decision makers to control than other variables (e.g. levee location or percentage of impervious surface).
	Possible	Blocked	Actual		
FLOW				Density of flows from ecosystems to beneficiaries represents the areas where the pathways of benefit provision concentrate. Actual flows depend on sinks and on the level of need of beneficiaries. Paths of provision vary greatly by service, but all services have a spatial path (sometimes to greatly different scales, as in the case of CO2 sequestration). Knowledge of provision paths is an asset in sustainable planning.	Locating development in areas of high flow density may reduce ES flows; undertaking conservation activities in these regions may increase ES flows. These areas are not the same as the source and destination areas, and their location is not obvious.

determines the list of ecosystem services of interest and their breakdown into benefits and beneficiaries of relevance to the area and the goals. In **Step 2,** data needs for modelling are determined, and all available data are retrieved and harmonized. This step again uses the ARIES ontologies to determine data needs in the context. Users have access to all metadata and are able to upload missing or substitution data. All datasets are converted to a common representation (in terms of units, resolution, spatial projection etc.) automatically, using their semantic annotations as a guide (Villa 2001; Kiryakov, Popov et al. 2003; Villa 2007; Villa, Athanasiadis et al. 2007; Villa 2009; Villa, Athanasiadis et al. 2009). The output is used in **Step 3** to build probabilistic models and (when possible) trained to data. ARIES builds Bayesian network models of **provision**, **source** and **sink** (depletion of benefit along its path to the beneficiary) for each benefit, using its model base and an AI-assisted iterative process (briefly outlined later). These models are “trained” to data if calibration data are available; if not, their prior probabilities are determined using expectation maximization (Dempster, Laird et al. 1977) based on similar areas where models have been previously computed. In **Step 4**, the Bayesian models are run and a flow model uses their results as input to assess the actual delivery of services to beneficiaries. This flow analysis (Table 1) determines what areas are critical to the *delivery* of the service and what portion of the theoretical provision actually reaches the intended beneficiaries. **Step 5** consists of an integrated value assessment and (when required) economic valuation. This phase, still in development at the time of this writing, computes models for a *set* of services of interest, taking into account mutual dependencies between services. Multiple ecosystem service results can then be paired with priority weights stated by the user, in a multiple criteria analysis that will yield maps of the concordance of the computed flows of ES with the levels of provision desired by the user. Such maps can be considered “abstract” quantification of relative value. Lastly, the ES flow information can be used to build a transfer function to translate previously assessed economic values for specific benefits into estimated valuation portfolios when that is required by the users, bridging to economic valuation. The transfer function operates on the aggregated values retrieved from our Ecosystem Services Database (Villa, Ceroni et al. 2007) with the help of a neural network classification algorithm that identifies most likely candidates based on ecological and economic similarities between the source and destination areas.

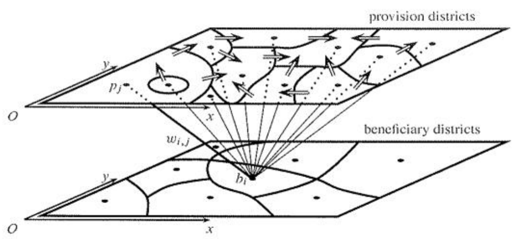


Figure 3. Illustration of the GSSM approach proposed to handle flow problems. Each source district (top layer) is generated from an unsupervised pattern recognition algorithm using feature data obtained from the knowledge base. Each district is described using a multi-scale model. Here Pj denotes the estimated provision from source district *j*, $W_{i,j}$ denotes the fractional gain in use from P_j to *i* (on the lower layer). The use districts will often correspond to the distribution of various economic and political benefits. As many ecosystem processes are intrinsically related to flow of carriers across the landscape, estimation of $w_{i,j}$ may require an additional transport or agent-based model. For example, in order to assess flood prevention as an ecosystem service, a hydrological model can be used to estimate the water runoff and soil absorption. The double arrows between adjacent provision districts signify the flux of such carriers.

As mentioned, probabilistic models drive all static assessments (source, use and sink); this class of models has been chosen based on being light on the assumptions, best suited for data-driven machine learning and most useful in decision making where explicit uncertainty is valued. The multiple-scale source/sink dynamics that is crucial to flow models is modeled by processing independently scaled source, sink and destination probabilistic surfaces into *flow districts* (Figure 3) based on the scales of the processes of production and use The trajectory of specified carriers (e.g. CO2 or floodwater) is then simulated as it propagates through the mesh of flow districts according to carrier-specific propagation rules. This approach (Johnson, Villa et al. forthcoming), code-named Generalized Source-Sink Modeling (GSSM, Figure 3) uses functionally defined plug-in sub-models that are passed to specific benefit models to simulate carriers that behave in different ways. For example, the flood model routes floodwater through the landscape using information such as porosity, slope and land cover. The aesthetic view model runs a line-of-sight algorithm from source to user using a distance-related damping factor and depleting aesthetic value along line of sight as visual blight or obstructions are encountered. Each flow model exposes few selected parameters to the user (e.g. intensity of rainfall events or transparency determined by airborne particulates) to enable simple user-driven scenario analysis. More sophisticated scenarios can be investigated by setting evidence for selected variables in the source, sink or use models (e.g. annual temperature) to investigate likely effects of policy or global changes. Specific case studies in ARIES include predefined scenario configurations that reflect known scenarios of interest, e.g. IPCC climate predictions (IPCC ; International Panel for Climate Change (IPCC) 2007). Such scenarios can be studied by simply selecting them from a list and compared with the baseline scenario produced.

At the time of this writing, ARIES incorporates working models (provision, use, sink and flow) for CO2 sequestration and storage, aesthetic view, proximity to open space and recreation; models for flood protection, water provision and soil retention are on their way to completion. The remaining services for the initial release (food provision from biodiversity and agriculture) will be completed by March 2010 along with a few site-specific services (including the multi-faceted services provided by salmon in the Puget Sound).

Economic valuation

Along with providing more realistic views of ecosystem service provision and use, these flow maps can also enable improved value transfer. A better understanding of the relative strength of flow can identify regions more likely to provide higher or lower levels of value (Boyd and Wainger 2003). Indeed the flow of benefits is the only quantity that relates supply and demand and is a natural candidate for a quantitative statement of value. In order for a flow of benefit to exist, a potential for provision must coexist with a need for use; the marginal value is determined by the "difference of potential" between the two sides, and is likely to be monotonically related to the quantified potential flows. This relationship is best modeled as non-linear, in a form that depends on a parameter of criticality of supply: no criticality determines a linear relationship between marginal value and flow of benefits, simplifying to a classical supply/demand model; if criticality is nonzero, approaching a critical threshold makes marginal value grow asymptotically. The value transfer engine under development for ARIES uses the quantitative assessment of flows and estimates of critical thresholds to appropriately mediate values from existing studies to an area under investigation.

Summary and future work

By explicitly demonstrating spatial links from ecosystems to people and the strength of the flow of ecosystem services, we can better demonstrate how people gain value from ecosystem services. Beyond demonstrating the value of ecosystem services to individuals, improved maps of provision, use, and benefit flows can help guide various policy applications for ecosystem services. This can lead to both fuller appreciation of value by the groups that benefit most from nature's services, and a better body of knowledge to enable sound decision making by society.

The outputs of an ARIES session have numerous practical uses for conservation and economic development planning. Notably, they can show which regions are critical to maintaining the supply and flows of particular benefits for specific beneficiary groups. By prioritizing conservation and restoration activities around sources and sinks for particular services, benefit flows may be maintained or increased. Similarly, focusing development or extractive resource use outside these regions can prevent degradation of benefit flows. The impacts of proposed projects on human well-being can be more fully evaluated, as improvements or declines in ecosystem services received by specific populations can be demonstrated. By identifying parties that benefit from or degrade benefit flows, these maps can also provide guidance for potential beneficiary-pays or polluter-pays based payments for ecosystem services (PES) programs. Finally, specific maps for an ecosystem or beneficiary group of interest can also be generated. Such maps can show either 1) the parts of the landscape from which a given beneficiary's benefits are derived, or 2) the beneficiary groups receiving benefits from a particular ecosystem region of interest (Johnson et al. unpublished).

We have to date mapped only the spatial dynamics of carbon sequestration and storage, aesthetic views and aesthetic proximity. However, upcoming work will enable the mapping of a number of other ecosystem services, including aesthetic proximity value, flood regulation, soil retention, and the provision of food. Another forthcoming area of application of ARIES is marine and coastal ecosystem services. Analysis of multiple ecosystem services can enable system users to overlay services, identifying areas that provide multiple "stacked," "bundled," or "co-benefit" services and to compare tradeoffs between services (Chan et al. 2006, Nelson et al. 2009). Such analysis can provide critical information to developers of emerging ecosystem service markets, especially in cases where financial incentives only exist for a single service, such as in emerging carbon markets or watershed credit trading programs. In these cases, the ARIES approach can help identify potential sources of demand for added services, expanding the breadth of the market and potential conservation financing.

Accounting for multiple ecosystem services can also help to avoid unintended outcomes, such as cases where maximizing a single marketed ecosystem service could reduce the flows of other services (Hansson et al. 2005, Jackson et al. 2005).

Understanding the flow pattern of benefits from ecosystems to people is a problem that has eluded past work in ecosystem services. For many authors, the flow problem has been expressed as a "spatial mismatch" between ecosystem service provision and use (Hein et al. 2006, Costanza 2008). By explicitly demonstrating spatial links from ecosystems to people and the strength of the flow of ecosystem services, we can better demonstrate how specific beneficiary groups gain value from ecosystem services. Particularly in the developed world, the beneficiaries of ecosystem services are often unaware of their dependence on ecosystems. Mapping of the beneficiaries of ecosystem services and the spatial flows of services are important steps in raising awareness of the value of ecosystem services. This can lead to both fuller appreciation of value by the groups that benefit most from nature's services, and a better body of knowledge to enable sound decision making by society.

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References cited

Beier, C. M., T. M. Patterson, et al. (2008). "Ecosystem services and emergent vulnerability in managed ecosystems: A geospatial decision-support tool." Ecosystems **11**(6): 923-938.

Boyd, J. and S. Banzhaf (2007). "What are ecosystem services? The need for standardized environmental accounting units." Ecological Economics **63**: 616-626.

Boyd, J. and L. Wainger (2003). Measuring ecosystem service benefits: The use of landscape analysis to evaluate environmental trades and compensation. . Washington, DC, Resources for the Future.

Carpenter, S. R., Castilla, J.C., deGroot, R.S., Mooney, H., Naeem, S., Noble, I., Zhiyun, O., Reid, W., Turpie, J., William, M., Shidong, Z. (2003). Ecosystems and their Services. Millennium Ecosystem Assessment: Ecosystems and Human well-being: a Framework for Assessment. 245 pp. NY, Island press**:** 49-70.

Costanza, R. (2008). "Ecosystem services: Multiple classification systems are needed. ." Biological Conservation **141**: 350-352.

Costanza, R., R. dArge, et al. (1997). "The value of the world's ecosystem services and natural capital." Nature **387**(6630): 253-260.

Cowell, R. G., A. P. Dawid, et al. (1999). Probabilistic Networks and Expert Systems. New York, Springer.

Daily, G. (1997). Nature's Services: Societal Dependence on Natural Ecosystems. Washington, DC, Island Press.

DeGroot, R. S., M. A. Wilson, et al. (2002). "A typology for the classification, description and valuation of ecosystem functions, goods and services." Ecological Economics **41**: 393-408.

Dempster, A. P., N. M. Laird, et al. (1977). "Maximum Likelihood from Incomplete Data via the EM Algorithm." Journal of the Royal Statistical Society. **39**(1): 1-38.

Farber, S., R. Costanza, et al. (2006). "Linking ecology and economics for ecosystem management." Bioscience **56**(2): 121-133.

Fisher, B., K. Turner, et al. (2006). "Ecosystem Services and Economic Theory: Integration for policy-relevant research." Ecological Applications **18**(8): 2050-2067.

Gruber, T. R. (1995). "Toward principles for the design of ontologies used for knowledge sharing." International Journal of Human-Computer Studies **43**(5-6): 907-928.

Hein, L. and E. van Ierland (2006). "Efficient and sustainable management of complex forest ecosystems." Ecological Modelling **190**(3-4): 351-366.

International Panel for Climate Change (IPCC) (2007). Climate Change 2007: synthesis report.

IPCC Intergovernmental Panel on Climate Change.

Johnson, G. W., F. Villa, et al. (forthcoming). Generalized source-sink models: a new instrument to conceptualize ecosystem service flows.

Kiryakov, A., B. Popov, et al. (2003). "Semantic annotation, indexing, and retrieval. ." Lecture Notes in Computer Science

Science **2870**: 484–499.

Kremen, C. and R. S. Ostfeld (2005). "A call to ecologists: measuring, analyzing, and managing ecosystem services." Frontiers in Ecology and the Environment **3**(10): 540-548.

Madin, J., S. Bowers, et al. (2007). "An ontology for describing and synthesizing ecological observation data." Ecological Informatics **2**: 279-296.

Millennium Ecosystem Assessment (2002). Ecosystem and Human well-being: a Framework for Assessment. NY, Island Press.

Mooney, H. A., A. Cropper, et al. (2004). "The millennium ecosystem assessment: what is it all about?" Trends in Ecology & Evolution **19**(5): 221-224.

Naidoo, R., A. Balmford, et al. (2008). "Global mapping of ecosystem services and conservation priorities." Proceedings of the National Academy of Sciences of the United States of America **105**(28): 9495-9500.

Naidoo, R. and T. H. Ricketts (2006). "Mapping the economic costs and benefits of conservation. ." PLOS **4**(11): 2153-2164.

Nelson, E., G. Mendoza, et al. (2009). "Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales." Frontiers in Ecology and the Environment **7**(1): 4-11.

Pereira, E., C. Queiroz, et al. (2005). "Ecosystem services and human well-being: a participatory study in a mountain community in Portugal." Ecology and Society **10**(2): -.

Tallis, H. and S. Polasky (2009). "Mapping and Valuing Ecosystem Services as an Approach for Conservation and Natural-Resource Management." Annals of the New York Academy of Sciences **1162**: 265-283.

UVM Ecoinformatics Collaboratory. (2009). "ARIES: ARtificial Intelligence for Ecosystem Services.", from http://ecoinformatics.uvm.edu/aries.

Villa, F. (2001). "Integrating modelling architecture: a declarative framework for multi-paradigm, multi-scale ecological modelling." ECOLOGICAL MODELLING **137**(1): 23-42.

Villa, F. (2007). "A semantic framework and software design to enable the transparent integration, reorganization and discovery of natural systems knowledge." Journal of Intelligent Information Systems **29**(1): 79-96.

Villa, F. (2009). Semantically-driven meta-modelling: automating model construction in an environmental decision support system for the assessment of ecosystem services flow.

Information Technology in Environmental Engineering. I. N. Athanasiadis, P. A. Mitkas, A. E. Rizzoli and J. Marx Gomez. New York, NY, Springer**:** 23-36.

Villa, F., I. N. Athanasiadis, et al. (2007). An Ontology for the Semantic Modelling of Natural Systems. 15th Annual International Conference on Intelligent Systems for Molecular Biology (ISMB) & 6th European Conference on Computational Biology (ECCB). Vienna.

Villa, F., I. N. Athanasiadis, et al. (2009). "Modelling with knowledge: a review of emerging semantic approaches to environmental modelling. ." Environmental Modelling & Software **24**: 577-587.

Villa, F., M. Ceroni, et al. (2007). "Intelligent Databases assist transparent and sound economic valuation of ecosystem services." Environmental Management **39**: 878-899.

Waage, S., E. Stewart, et al. (2008). Measuring Corporate Impact on Ecosystems: A Comprehensive Review of New Tools. San Francisco, CA, Business for Social Responsibility**:** 18.

Wallace, K. J. (2007). "Classification of ecosystem services: Problems and solutions." Biological Conservation **139**: 235-246.

Wilson, M. A. and S. R. Carpenter (1999). "Economic valuation of freshwater ecosystem services in the United States: 1971-1997." Ecological Applications **9**(3): 772-783.