Economía Agraria y Recursos Naturales. ISSN: 1578-0732. Vol. 11,1. (2011). pp. 83-98

Scientific instruments for climate change adaptation: estimating and optimizing the efficiency of ecosystem service provision

Ferdinando Villa[1], Ken Bagstad[2], Gary Johnson[2], Brian Voigt[2]

ABSTRACT: Adaptation to the consequences of climate change can depend on efficient use of ecosystem services (ES), i.e. a better use of natural services through management of the way in which they are delivered to society. While much discussion focuses on reducing consumption and increasing production of services, a lack of scientific instruments has so far prevented other mechanisms to improve ecosystem services efficiency from being addressed systematically as an adaptation strategy. This paper describes new methodologies for assessing ecosystem services and quantifying their values to humans, highlighting the role of ecosystem service flow analysis in optimizing the efficiency of ES provision.

KEYWORDS: Ecosystem services, flow analysis, Bayesian modeling, spatial analysis.

JEL classification: Q01, Q54, Q55, Q57.

Herramientas científicas para la adaptación al cambio climático: estimo y optimización de la eficiencia de provisión de los servicios de ecosistemas

RESUMEN: Adaptación a las consecuencias del cambio climático puede depender de un uso eficiente de los servicios de los ecosistemas (SE): un mejor uso de los servicios naturales a través del manejo de la forma en que se entregan a la sociedad. Aunque mucha discusión ha sido centrada en reducir el consumo y aumentar la producción de servicios, una falta de instrumentos científicos nos ha impedido el tratamiento sistemático de otros mecanismos para mejorar la eficiencia de los servicios de ecosistemas como estrategia de adaptación. Se describen nuevas metodologías para cuantificar los servicios de los ecosistemas y su valor para los seres humanos, con referencia especial a la importancia de cuantificar el flujo de servicios ambientales para optimizar la eficiencia de provisión de SE.

PALABRAS CLAVES: Servicios de ecosistemas, análisis de flujo, modelación Bayesiana, análisis espacial.

Clasificación JEL: Q01, Q54, Q55, Q57.

[1] Basque Centre for Climate Change (BC3), IKERBASQUE, Basque Foundation for Science.
[2] Ecoinformatics Collaboratory, Gund Institute for Ecological Economics, University of Vermont.

Acknowledgements: Funding for this work was provided by the US National Science Foundation, grant 9982938. An initial marine component was funded by UNEP-WCMC. We thank the ARIES partner organizations of Conservation International (CI) and Earth Economics (EE) and the many collaborators at case study locations for support, data and knowledge sharing, and contributing to improving the understanding of regional ecosystem services dynamics.
Contact author: Ferdinando Villa. E-mail: ferdinando.villa@bc3research.org.

Recibido en febrero de 2011. Aceptado en agosto de 2011.

1. Introduction

The concept of Ecosystem Services (Daily 1997; Carpenter *et al*., 2003; Kremen and Ostfeld, 2005) brings together the many ways that nature contributes to human well-being into a cohesive scientific view. Focusing on both the biophysical side of ES provision and the economic side of ES use can allow society to better balance the "nature vs. the economy" equation, improving management and governance (Millennium Ecosystem Assessment, 2002). Unfortunately, the scientific tools required to support quantification, mapping and valuation of ES have lagged behind the popularity of the concept, making it difficult to use ES productively as a basis for scientific investigation and accurate decision- and policy-making (Fisher *et al.,* 2006; Boyd and Banzhaf, 2007; Wallace, 2007). Virtually all methods employed or proposed (Costanza *et al.,* 1997; Wilson and Carpenter, 1999; Farber *et al.,* 2006; Nelson *et al.,* 2009; Tallis and Polasky, 2009) to quantify ES and their values convert proxy categorical information, chiefly land cover class, into coarse assessments of value or potential provision by using aggregated coefficients. Such approaches ignore the complex, multi-scale dynamics of ES provision, use and flow, and do not offer enough accuracy to inform decisions or allow for quantitative, spatially explicit scenario analysis.

An integrated methodology for ES assessment based on the explicit quantification of spatial flows of benefits from nature to humans has been in developement since 2007. This methodology, called ARIES (ARtificial Intelligence for Ecosystem Services), has been implemented as a web-accessible technology founded on advanced ecoinformatics. This design choice aims to support a more accurate, science-based ES analysis through models that are tailored to the specifics of each case study but without increasing the complexity and cost of ES analysis for the user. This method and the corresponding rapid assessment software toolkit can currently handle a sizable cross-section of the ES problem area (Table 1); the methods and models are being fine-tuned in case studies in Madagascar, the Eastern and Western USA, Mexico, Spain, and elsewhere. These pilot applications are taking place in sectors as diverse as conservation, industry, and government from municipal to national level (Waage *et al.,* 2008).

TABLE 1

Current ecosystem service modules in ARIES. The toolkit also allows integrated assessment based on Spatial Multiple Criteria Analysis of multiple module results

ARIES module	Beneficiary types	Areas of testing
Aesthetic viewsheds	Residential users Recreational users	NW/NE/SW USA
Open space proximity	Residential users	NW/SW USA
Coastal flood regulation	Coastal populations Coastal assets	Madagascar
Subsistence fisheries	Subsistence-dependent coastal populations	Madagascar
Sediment regulation	Farm users (deposition) Farm users (erosion control) Hydropower generation	Madagascar, Dominican Republic, NW USA
Flood regulation	Farm users Public assets Private assets General population	NW USA
Recreation	Birdwatchers Wildlife watchers Hunters	SW/NE USA
Carbon sequestration and storage	General population Greenhouse gas emitters	Madagascar, NW/SW/NE USA
Water supply	Residential users Farm users Industrial users Hydropower generation	NW/SW USA, Madagascar, Veracruz Mexico

Focusing on flows of ecosystem services allows investigators and decision makers to compute not only the potential provision, but also the specific proportion of it that actually gets to users and, conversely, the part that remains unutilized. This opens the door to new, fine-tuned strategies for climate change adaptation based not only on the increase in service provision or on the reduction in consumption but also on the increased efficiency of ecosystem service delivery. This is only possible when the delivery mechanisms are understood and quantitative models of the process are available. The ARIES methodology is the first systematic tool to address efficiency problems in ES delivery. This article discusses the key aspects of ARIES and provides an introduction to ES flow analysis as a support methodology for climate change adaptation.

2. A new scientific theory of Ecosystem Services

The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2002; Mooney *et al.,* 2004; Pereira *et al.,* 2005) broke ES down into four categories: 1) "supporting services," the ecological processes and functions that generate other ES; 2) "regulating services", which maintain global to local conditions at levels appropriate for human survival; 3) "provisioning services", which offer physical resources directly contributing to human well-being; and 4) "cultural services", which meet psychological, emotional, and cultural needs. The MA classification has been very useful in describing how nature satisfies different domains of human well-being. However, recent authors have noted that the MA ES 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 precisely link specific benefits to specific human beneficiaries of ES. Better definition and mapping of these benefits and beneficiaries could improve ES valuation, environmental accounting (Boyd and Banzhaf, 2007), identification of winners and losers in conservation and development choices, and support payments for ecosystem service programs.

From a mapping perspective, the supply side of ES has been relatively well explored. A number of recent studies have used GIS modeling to measure the ecological factors contributing to the provision of ES (Naidoo and Ricketts, 2006; Beier *et al.,* 2008; Nelson *et al.,* 2009). These studies explore how ES provision varies across the landscape. However, far fewer studies have explicitly identified the demand side, or human beneficiaries (Hein *et al.,* 2006) or mapped those beneficiaries (Beier *et al.,* 2008). Yet the need for such mapping is becoming increasingly recognized (Naidoo *et al.,* 2008). Supply and demand side mapping is complex, since ES provision and use often occur across different spatial and temporal scales (Hein *et al.,* 2006). Other authors (Tallis and Polasky, 2009) clearly describe the "spatial flow problem" in ES. The ES research community has as yet been unable to move beyond "static maps" to consider the cross-scale flows of ES to different groups of human beneficiaries. Those attempts made so far to classify ES (Costanza, 2008) break them down into coarse categories based on how their benefits flow spatially to beneficiaries but stop short of providing a quantitative conceptualization. In order to advance ES assessment, we must start from the concepts of the MA framework, incorporate several of the above-mentioned key elements, and move towards ES science to quantify spatial and temporal flows of clearly identified benefits towards clearly identified beneficiaries.

3. Ecosystem service flow analysis

Many of the difficulties of modeling ES result from the diversity of the benefits that they produce. In particular:

1. Provision and use of ES happen at independent scales in space and time. Therefore, scale-explicit approaches are needed, and theoretical tools to tackle multi-scale systems are lacking.

2. The "currency" of ES benefit provision is rarely an easily modeled biophysical quantity. For the easier cases such as CO_2, quantification of its exchange between vegetation and atmosphere may be all that is needed to assess benefits of carbon sequestration. Quantitative modeling is much more complex for benefit mediated by hard-to-define currencies, such as cultural identity or avoided flood risk.
3. There is little clarity in the literature as regards a quantifiable definition of ES, their benefits, and the ES-related interactions between ecosystems and their human beneficiaries.

To address such difficulties, artificial intelligence techniques (such as machine reasoning and pattern recognition) can examine GIS data patterns and extract model knowledge from a stored knowledge base to best represent the situation at hand. The ARIES system is based on explicit descriptions that identify the individual benefits of ES, model each benefit independently, and then link each computed benefit to others. ARIES then builds ad-hoc, probabilistic Bayesian network models (Cowell *et al.,* 1999) to map ecological and socioeconomic factors contributing to the provision and use of ES. These models enable corresponding GIS data to be used to produce ES provision and use maps. Spatial flow models, explained in more detail later, are then used to identify the strengths of ES flows providing benefits from ecosystems to people.

Identifying and mapping beneficiaries was a key step in developing the ARIES system. We systematically define ES and their provision and use through *ontologies* (Villa *et al.,* 2009), which are computer-readable statements of knowledge. Ontologies are designed to create common, mathematically formalized language for abstract concepts and relationships, promoting consistent, precise, standardized understanding in these fields (Gruber, 1995; Madin *et al.,* 2007). Within ARIES, ontologies provide a knowledge base for a reasoning algorithm to extract models that are applied to data to quantify how ES are provided and used. More specifically, ontologies in ARIES specify:

1. A core vocabulary for ES, defining and classifying their general means of provision and use so that specific vocabularies can be built for specific services;
2. For each ES, 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 through space and promotes its transfer to humans (e.g., CO_2, floodwater, or aesthetic information).
3. For each benefit, the set of components of both the natural and human systems 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 data for modeling.

In ARIES, each service is defined by a carrier substance that moves across the landscape and determines the existence of the ecosystem service. Such carriers may be physical (e.g., water) or informational (aesthetic beauty or proximity to open space). In an ARIES session, the three fundamental maps of (1) source, (2) sink and (3)

use are computed using spatially explicit models. These maps are static in the sense that they provide a snapshot of the probabilities and amount of each of the following quantities at each point in the region of interest at the time represented in the data:

- **Source** areas where the carrier of the ecosystem service (e.g., water, fish or aesthetic beauty) is generated;
- **Sink** areas that can deplete the service carrier before it reaches a user;
- **Use** areas where users in need of the service are located.

The source, sink and use models are quantitative and probabilistic (see below) in the sense that they compute for each point a quantitative statistical distribution of the amounts of carrier that may be generated, depleted and used. Such models provide initial conditions for a spatially explicit, dynamic flow model which simulates the distribution of benefits across the landscape and collects statistics about how much of the service is used by the beneficiaries and where. The exact form of all models depends on the end user's context and is chosen by the ARIES system infrastructure using machine reasoning, on the basis of data availability and the physical nature of the ES (e.g., rival vs. non-rival nature of benefits, or the "preventive" vs. "provisioning" character of the services, Johnson *et al.,* 2010). ARIES differs from other approaches in not mandating a specific model form but tailoring each model to physical, socioeconomic and ecological characteristics of the area under analysis. Such decisions are taken by ARIES on the basis of the knowledge stored in its ontologies, using a reasoning algorithm that bases its inference on the available data. The ARIES ontologies are a distilled representation of ES knowledge extracted from literature, expert opinion and interviews with managers and stakeholders in many case study locations.

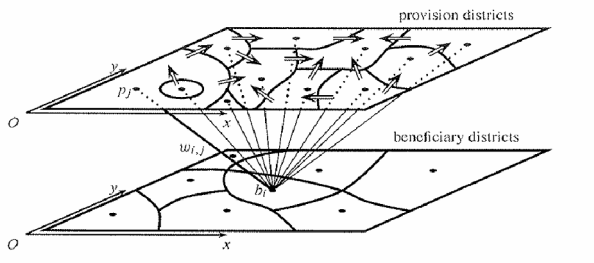
Because explicit uncertainty is critical for decision-making, ARIES employs probabilistic models (spatial Bayesian networks) to compute the provision, use, and sink surfaces for each benefit. The flow models propagate this uncertainty, so that each resulting map in ARIES can be associated with a corresponding map of uncertainty or reliability, which is of great value in transferring the results to policy recommendation. Users can modify variables of interest (such as land cover, vegetation type, annual mean temperature, and rainfall) to study their comparative effects in scenarios.

The steps in an ARIES session can be summarized as follows. In **Step 1,** benefits and beneficiaries are determined through an interactive process between the system and the user. The user draws the area of interest on a web-enabled interface (Figure 1), uploads it from a GIS file or selects the study area from a built-in gazetteer. The goals of the analysis (e.g., conservation planning or siting for planned development) are chosen by selecting a particular "entry point" into the ARIES toolkit. From this input, ARIES determines the list of ES of interest and their breakdown into benefits and beneficiaries of relevance to the area and the goals. In **Step 2** the data needs for modeling are determined, and available data are retrieved and harmonized. This step again uses the ARIES ontologies to determine data needs in the chosen context. Users have access to all metadata and are able to upload missing or substitute 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 (Kiryakov *et al.,* 2003; Villa *et al.,* 2007; Villa, 2009; Villa *et al.,* 2009). The output is used in **Step 3** to build probabilistic models. ARIES builds Bayesian network models of **source, sink** (depletion of benefits along their path to the beneficiary) and **use** 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 *et al.,* 1977) based on similar areas where models have been previously computed. In **Step 4**, the Bayesian models are run and their results are input into a flow model to assess the actual delivery of services to beneficiaries. This flow analysis (explained in more detail later) determines which areas are critical to the *delivery* of the service and what portion of the theoretical provision actually reaches the intended beneficiaries.

FIGURE 1

Illustration of the SPAN approach to ES flow mapping

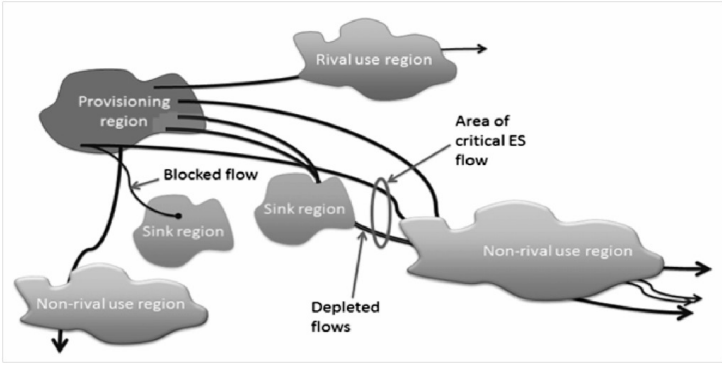


Each source district (top layer) is generated from an unsupervised pattern recognition algorithm using feature data obtained from the knowledge base. Each district is described using a multi-scale model. Here Pj denotes the estimated provision from source district j, Wi,j denotes the fractional gain in use from Pj to i (on the lower layer). The use districts often correspond to the distribution of various economic and political benefits. As many ecosystem processes are intrinsically related to the flow of carriers across the landscape, estimation of wi,j may require an additional transport or agent-based model. For example, in order to assess flood prevention as an ES, a hydrologic 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 assessment of source, use and sink (Figure 2); this class of models was chosen because it is light on expert assumptions, best suited for data-driven machine learning and most useful in decision making where uncertainty is valued. Specific case studies in ARIES include predefined scenario configurations that reflect known scenarios of interest, e.g., IPCC: climate predictions (IPCC, 2007). Such scenarios can be studied by simply selecting them from a list and compared with the baseline scenario produced.

FIGURE 2

A conceptual illustration of the component of the ARIES approach to ecosystem service modeling



Benefits (defined either as provision of beneficial goods or prevention of damaging factors) are generated in a provisioning region and reach use regions that can be rival (the use of the benefit reduces its availability for other beneficiaries) or non-rival. Along the path to the beneficiaries, the quantity of benefit carried can be depleted by sinks. The provision of benefits follows spatial trajectories that depend on the specific carrier. Regions of high concentration of such trajectories represent critical flow regions that require conservation efforts and may not coincide with either provision or use areas. Contact with rival users or sinks can either block or deplete flows available for other users, and can be considered beneficial or detrimental depending on the service type.

Flow modeling

The multiple-scale source/sink dynamics that are crucial to flow models are modeled by processing independently scaled source, sink, and destination probabilistic surfaces into *flow districts* (Figure 2) reflecting the spatial and temporal scaling of the processes of production and use. The trajectory of specified carriers (e.g., CO_2 or floodwater) is then simulated as they propagate through the mesh of flow districts according to carrier-specific propagation rules. This "Service Path Attribution Network" approach (SPAN, Figure 2, Johnson *et al.,* 2010) uses a family of routing sub-models that are assembled into benefit-specific 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 a 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 developed by setting evidence for selected variables in the models (e.g., annual temperature) to investigate likely effects of policy or global changes.

The flow model emphasizes service flows rather than their italicize production, reflecting the definition of ecosystem services given earlier. The SPAN algorithm discovers dependencies between provision and usage endpoints, spatial competition among users for scarce resources, and landscape effects on ecosystem service flows. As such it is particularly well-suited to identifying areas of inefficiency in transport or depletion of the carrier delivering the service. Particularly novel is the model's ability to identify regions critical to the preservation of benefit flows; such areas do not necessarily correspond to direct producers or users of the service.

SPAN models have been developed for a number of services (Table 1), which vary in scale of effect, mechanism of provision and use, and type of flow. The simulation of a SPAN model (see Johnson *et al.*, 2010 for details) accumulates weighted trajectories corresponding to the spatial route of the service carrier as it encounters beneficiaries and sinks.

Once the flow model has completed execution, the trajectories obtained are analyzed to determine the total amount of service that 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. Several results are produced by this path analysis:

Theoretical Source, Sink, Use values are the direct results of the initial source, sink, and use models; they represent the maximum potential supply, depletion, and demand for a service regardless of the flow paths that determine the amount of a service carrier that actually reaches the users. Theoretical source values are what traditional ES assessment is commonly focused on; as flow dynamics is not considered in any established methodology, the frequent complaint of over-valuation of ES could be attributed to the mistaken perception that all the theoretical source values are available for use and are therefore capable of generating value with 100% efficiency.

Possible Source, Sink, Use, Flow correspond to the 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.

Actual Source, Sink, Use, Flow are the 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.

Inaccessible Source, Sink, Use are computed as the differences between Theoretical and Possible values. These values represent unreachable source production, unutilized sinks, and unsaturated use capacity due to flow topology.

Blocked Source, Sink, Use, Flow are computed as the differences between Possible and Actual values. These values represent unreachable source production, unutilized sinks, and unsaturated user capacity due to sink and rival use effects.

The role of source, sink and use in value provision changes according to the nature of the service. The MA defined four broad categories of ecosystem services (provisioning, supporting, regulating, cultural). Those categories have been broadly questioned in the years since the publication of the MA. The reassessment conducted in ARIES reduces these categories to two (provisioning and preventive) as explicit models of the biophysical chain of ES provision make supporting services irrelevant, and the "cultural services" of the MA can be modeled consistently with provisioning services. We have chosen to use "preventive" vs. "regulating" to better highlight the dichotomy and to avoid confusion with the MA categorization.

For provisioning services, such as water supply or aesthetic enjoyment, the use values calculated in this stage represent met (or unmet) user demand, sinks are considered detrimental, and source regions are valued according to how much of the service that they produce 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 preventive services, such as flood or nutrient regulation, 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 can be used in combination with maps of the flow topology and density to target spatial planning decisions that seek 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.

Efficiency of service provision

Only the portion of the total potential provision that actually reaches users can be counted as actual value. As explained more rigorously in the previous section, this portion depends not just on provision and need but also on sinks, rival use, and flow patterns.

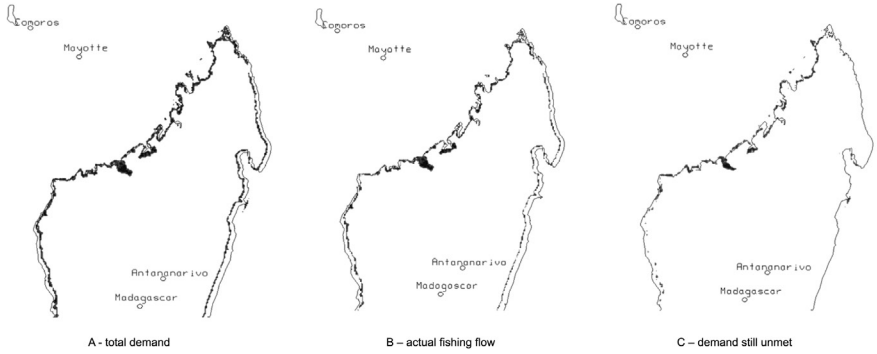
Preliminary results from ARIES show that in all ecosystem services, with the possible exception of carbon sequestration and storage, the actual value that reaches users differs greatly from the potential value. While this does not come as a surprise, current ecosystem service science is largely based on the quantification of provision, and the value of natural environments is commonly assessed based on theoretical calculations of the potential total only.

The negative consequences of climate change can be partially offset by strategies that maximize the realized value without impacting on climate and without necessarily pursuing higher production or lesser use. Flow analysis can be used to illuminate these strategies and follow up on their success. We illustrate this notion with an example from one of the ARIES case studies.

Figure 3 shows an example that highlights the new opportunities offered by ARIES in quantifying realized vs. potential value. The example is not directly related to climate change, but it illustrates the reasoning that can lead to development of informed adaptation strategies based on the development of scenarios that maximize efficiency. ARIES incorporates a climate change scenario module that automatically inserts data from user-selected IPCC scenarios in place of current records, offering a simple way to start exploring climate-centered policy solutions.

FIGURE 3

Partial results of the ARIES analysis of subsistence fisheries in Madagascar



The total potential subsistence fish harvest (totals for three fish species of known importance for subsistence fisheries, not shown) is combined with the assessment of need shown in A (based on poverty, population density and distance to coast) in a flow model that computes the actual delivery of the resource taking into account both the network of access path to shore and depletion of the resource due to estuary pollution. All quantitative values are shown in grey along with the coastline. The flow of fish to people based on modeling the capture of available fish by users that utilize roads of access to the shore is shown in B (in weight of fish moved from sea to people's dwellings). The map in C shows the portion of the total need (A) that the fishing shown in B cannot meet, identifying areas (mostly on the west coast) where subsistence of poor coastal population may be at risk. Policy decisions can optimize access roads and reduce pollution; quantitative analysis of such factors can help guide these decisions and monitor their successful implementation.

The potential value of fish resources for subsistence users in coastal areas in Madagascar is shown in 3-A; the model was computed using habitat suitability and abundance records alone. This potential, corresponding to the amount of fish available for subsistence of the coastal population, should ideally meet the subsistence needs shown in 3-B, computed by a beneficiary model that considers poverty, distance from the coast and other socio-economic factors.

The image in 3-C represents the need that is actually met, computed based on the results of the flow model, which moves the available fish resources along actual access paths to the shore, based on data compiled by the Malagasy government. It can be easily seen that the actual value of fish resources is much lower than the potential (less that 10% of the potential in preliminary calculations) when the actual process

of accessing the resource is modeled, and that a large percentage of the population may still be below critical thresholds for nutrition despite the theoretical availability of enough fish for sustenance (this model does not currently consider such important real-life factors as the proportion of fish allocated to commercial and subsistence harvests). In preliminary runs, a slight increase in the parameter that determines the accessibility of the roads and paths to the shore results in a large improvement in the value of fisheries, bringing more of the potential resource within reach of coastal populations. The analysis can highlight "problem" areas directly by mapping the unsatisfied need (Figure 3-D), and give a quantitative estimate of distance from sustenance goals or from the possibility of commercial exploitation of a resource.

Although the preliminary results shown must be considered as demonstrative, and do not directly involve climate projections, they can serve as an example of the quantitative understanding of the need for a service and of the mechanisms that link potential provision to satisfying actual need. It is easy to see how scenarios aimed at maximizing efficiency can be computed with relative ease once this kind of ecosystem service modeling is available, allowing the planning of sustainable quotas and allocation of commercial fisheries in precise detail. Such scenarios can be aimed at improving efficiency of service delivery without reducing demand (an obvious requirement in conditions of critical scarcity), or impacting climate by attempting to increase production. Similar arguments can be made for other services in the ARIES areas of intervention. For example another Madagascar case study (ARIES, 2011), not shown here, clearly shows how a mangrove protection program could greatly increase the storm protection value of existing natural features, leading to cost-effective disaster protection for coastal populations and assets. ARIES preliminary results from many case studies reveal that the effect of sinks and flow dynamics on the efficiency of service delivery is almost always very important; this creates ample margins of opportunity for policy makers to identify efficiency-based strategies once appropriate quantitative instruments are available.

4. Discussion and prospects

Beyond demonstrating the value of ES to individuals, mapping provision, use, and benefit flows can help guide various policy applications for ecosystem services. This can lead to both a 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 most common arguments on sustainable development focus on either increasing the productivity of critical ecosystem services or reducing overuse of resources. While these arguments are still relevant, the ability to quantify with reasonable precision how and how much of a service gets lost on its way to users and how much will not reach them due to flow dynamics suggests that flow analysis may become a powerful tool in the struggle for sustainable living.

Instruments such as ARIES, which explicitly demonstrate spatial links from ecosystems to people and quantify the strength and spatial pattern of ES flows, can greatly help to inform a sustainability strategy based on efficiency. Such a strategy must be pursued in the context of a larger-scale trade-off analysis, ensuring that the increased uptake of one ES does not jeopardize sustainable use of other, related ES. A desirable property of such an "adaptation through efficiency" strategy is for its numeric predictions to be usable also for follow-up, providing at the same time the quantitative understanding to inform policy and the natural indicators to measure its success.

The outputs of an ARIES session have numerous practical uses for sustainable development in the face of global change. 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 beneficiary-pays or polluter-pays based payments for ecosystem service (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 that receive benefits from a particular ecosystem region of interest.

At the time of writing, ARIES contains preliminary spatial dynamic models for nine ecosystem services. Along with the fisheries and coastal protection models discussed for Madagascar, it includes models of carbon sequestration and storage, aesthetic views, open space proximity, flood regulation, sediment regulation, recreation and water supply. These models work in several locations around the globe. In addition, analysis of multiple ES 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 for developers of ES markets, especially in cases where financial incentives only exist for a single service, such as in emerging carbon or watershed credit trading markets. 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 on ecosystem services. For many authors, the flow problem has been expressed as a "spatial mismatch" between ES 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 ES, 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 a 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.

References

ARIES web site (2011). Online: www.ariesonline.org.

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

Boyd, J. and Banzhaf, S. (2007). "What are ecosystem services? The need for standardized environmental accounting units". *Ecological Economics,* 63(2-3): 616-626.

Carpenter, S.R., Castilla, J.C., de Groot, R.S., Mooney, H., Naeem, S., Noble, I., Zhiyun, O., Reid, W., Turpie, J., William, M. and Shidong, Z. (2003). "Ecosystems and their Services". In *Millennium Ecosystem Assessment: Ecosystems and Human well-being: a Framework for Assessment*. Island Press, New York: 49-70.

Chan, K.M.A., Shaw, M.R., Cameron, D.R., Underwood, E.C. and Daily, G.C. (2006). "Conservation planning for ecosystem services." *PLOS Biology,* 4(11): 2138-2152.

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

Costanza, R., d'Arge, R., DeGroot, R., Farber, S., Grasso, M., Hannon, B., Kimburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P. and Van Den Belt, M. (1997). "The value of the world's ecosystem services and natural capital". *Nature,* 387(6630): 253-260.

Cowell, R.G., Dawid, A.P., Lauritzen, S.L. and Spiegelhalter, D.J. (1999). *Probabilistic Networks and Expert Systems*. Springer, New York.

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

Dempster, A.P., Laird, N.M. and Rubin, D.B. (1977). "Maximum likelihood from incomplete data via the EM algorithm". *Journal of the Royal Statistical Society*, 39(1): 1-38.

Farber, S., Costanza, R., Childers, D.L., Erickson, J., Gross, K., Grove, M., Hopkinson, C.S., Kahn, J., Pincetl, S., Troy, A., Warren, P. and Wilson, M. (2006). "Linking ecology and economics for ecosystem management". *Bioscience,* 56(2): 121-133.

Fisher, B., Turner, K., Zylstra, M., Brouwer, R., DeGroot, R., Farber, S., Ferraro, P., Green, R., Hadley, D., Harlow, J., Jefferiss, P., Kirkby, C., Morling, P., Mowatt, S., Naidoo, R., Paavola, J., Strassburgh, B., Yu, D. and Balmford, A. (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.

Hansson, L., Brönmark, C., Anders Nilsson, P. and Åbjörnsson, K. (2005) "Conflicting demands on wetland ecosystem services: nutrient retention, biodiversity, or both?". *Freshwater Biology,* 50: 705-714.

Hein, L. and Van Ierland, E. (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.

Jackson, R.B., Jobbágy, E.G., Avissar, R., Baidya Roy, S., Barrett, D.J., Cook, C.W., Farley, K.A., le Maitre, D.C., McCarl, B.A. and Murray, B.C. (2005). "Trading water for carbon with biological carbon sequestration". *Science,* 310: 1944-1947.

Johnson, G.W., Bagstad, K., Snapp, R. and Villa, F. (2010). "Service Path Attribution Networks (SPANs): spatially quantifying the flow of ecosystem services from landscapes to people". *Lecture Notes in Computer Science,* 6016: 238-253.

Kiryakov, A., Popov, B., Terziev, I., Manov, D. and Ognyanoff, D. (2003). "Semantic annotation, indexing, and retrieval". *Lecture Notes in Computer Science,* 2870: 484-499.

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

Madin, J., Bowers, S., Schildauer, M., Krivov, S., Pennington, D. and Villa, F. (2007). "An ontology for describing and synthesizing ecological observation data". *Ecological Informatics,* 2(3): 279-296.

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

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

Naidoo, R., Balmford, A., Costanza, R., Fisher, B., Green, R.E., Lehner, B., Malcom, T.R. and Ricketts, T.H. (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 Ricketts, T.H. (2006). "Mapping the economic costs and benefits of conservation". *PLOS,* 4(11): 2153-2164.

Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, R., Chan, K.M.A., Daily, G.C., Goldstein, J., Kareiva, P.M., Londsdorf, E., Naidoo, R., Ricketts, T.H. and Shaw, M.R. (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., Queiroz, C., Pereira, H.M. and Vicente, L. (2005). "Ecosystem services and human well-being: a participatory study in a mountain community in Portugal". *Ecology and Society,* 10(2): 14. Online.

Tallis, H. and Polasky, S. (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.

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". *Environmental Science and Engineering*, Part 1: 23-36. Springer, New York.

Villa, F., Athanasiadis, I.N. and Johnson, G. (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., Athanasiadis, I.N. and Rizzoli, A.E. (2009). "Modelling with knowledge: a review of emerging semantic approaches to environmental modelling". *Environmental Modelling and Software,* 24(5): 577-587.

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

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

Wallace, K.J. (2007). "Classification of ecosystem services: Problems and solutions". *Biological Conservation,* 139(3-4): 235-246.

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