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Article

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Measuring, modeling and mapping ecosystem services in the Eastern Arc Mountains of Tanzania

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Abstract

In light of the significance that ecosystem service research is likely to play in linking conservation activities and human welfare, systematic approaches to measuring, modeling and mapping ecosystem services (and their value to society) are sorely needed. In this paper we outline one such approach, which we developed in order to understand the links between the functioning of the ecosystems of Tanzania's Eastern Arc Mountains and their impact on human welfare at local, regional and global scales. The essence of our approach is the creation of a series of maps created using field-based or remotely sourced data, data-driven models, and socio-economic scenarios coupled with rule-based assumptions. Here we describe the construction of this spatial information and how it can help to shed light on the complex relationships

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between ecological and social systems. There are obvious difficulties in operationalizing this approach, but by highlighting those which we have encountered in our own case-study work, we have also been able to suggest some routes to overcoming these impediments.

Keywords
biodiversity, carbon storage, Eastern Arc Mountains, economic valuation, ecosystem services, Tanzania

I Introduction

Current global concern regarding climate change, energy supply, food and water security and the loss of biodiversity has made it clear that a scientifically robust, policy-oriented understanding of how these issues are interrelated will be essential for developing effective solutions (Holdren, 2008). The concept of ecosystem services is one construct for understanding how changes to our natural environment impact our welfare. How climate change will affect agricultural yields and water availability, how biofuel-crop expansion will affect biodiversity, and how growing human populations and economies will affect forest cover, are all examples of the important questions that fall under the rubric of ecosystem services research. In fact the use of the term 'ecosystem services' as a research framework has become much more prominent in the academic literature over the past decade (Carpenter et al., 2006; Fisher et al., 2009), the publication of the Millennium Ecosystem Assessment (MA, 2005), and the newly formed Intergovermental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2010) has securely tied the importance of well-functioning ecosystems to sustainable human welfare.

In light of the significance that ecosystem service research is likely to play in linking conservation activities and human welfare, systematic approaches to measuring, modeling and mapping ecosystem services (and their value to society) are urgently needed (Carpenter et al., 2006). In this paper we outline one such approach, which we developed in order to understand the links between the functioning of the ecosystems of Tanzania's Eastern Arc Mountains and their impact on human welfare at local, regional, and global scales. The essence of our approach is the creation of a series of maps created using field-based or remotely sourced data, data-driven models, and socio-economic scenarios coupled with rule-based assumptions. Here we describe the construction of this spatial information and how it can help to shed light on the complex relationships between ecological and social systems. We highlight some of the difficulties of employing this approach, as well as some of the insights gained. While this project – Valuing the Arc (VtA) – is still a work in progress, we are able to illustrate some of the policy-ready outputs of such an approach.

Below we describe the biological and socio-economic importance of the Eastern Arc Mountains, the services they deliver, the sequence of steps in the mapping exercises, the importance of scenario-building, and a brief example of how to apply such an ecosystem services approach to linking conservation, human welfare, and decision-making.

II Eastern Arc Mountains, Tanzania

The Eastern Arc Mountains of Tanzania (EAM) comprise 13 mountain blocks stretching the length of the country (Figure 1). The EAM is a globally important ecoregion (Burgess et al., 2004, 2006), and constitutes a large part of one of the world's 34 hotspots of biological diversity (Mittermeier et al., 2004). It is home to around 550 endemic plants and more than 90 endemic vertebrates (see Burgess et al., 2007, for more in-depth information on biological importance of EAMs). In addition to this unique biodiversity,

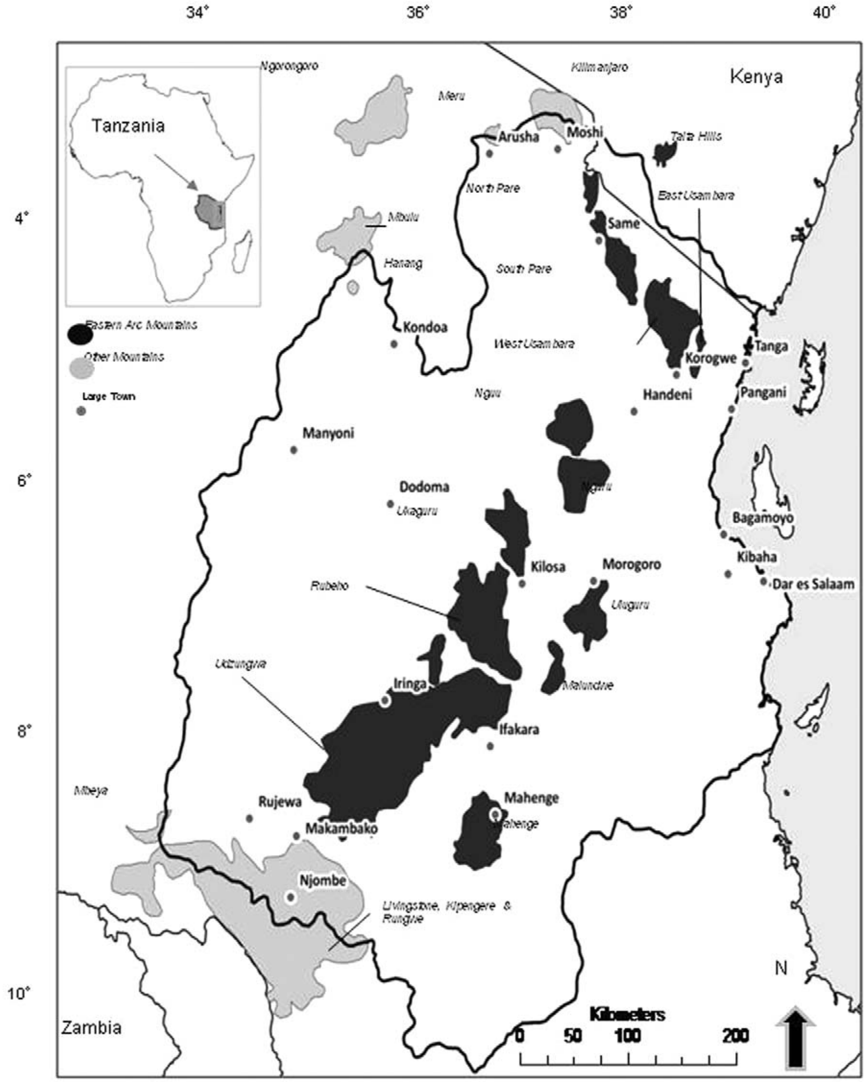

Figure 1. Eastern Tanzania showing the Eastern Arc Mountain chain. While the focal ecosystem service production areas are outlined in black, the beneficiaries stem from local to global.

these mountains also provide a range of ecosystem services and related human benefits at local, regional, and global scales – including timber and fuel wood; water for irrigation, domestic use and hydroelectricity; carbon storage; medicinal plants and other minor forest products; and nature-based tourism (Doggart and Burgess, 2005).

At the same time this is an area of rapid land-cover change, having lost 11% of its primary forests and 41% of its woodlands since 1975 (Mbilinyi et al., 2006). This conversion is driven by clearance for farmland, as well as increasing demand for timber and fuel wood. These pressures, subsistence and commercial, are rational in the short term, especially in a country where 44% of the population is food-insecure (UN, 2005) and over 90% of household energy comes from burning biomass (Sheya and Mushi, 2000), but they seem unlikely to provide a sustainable

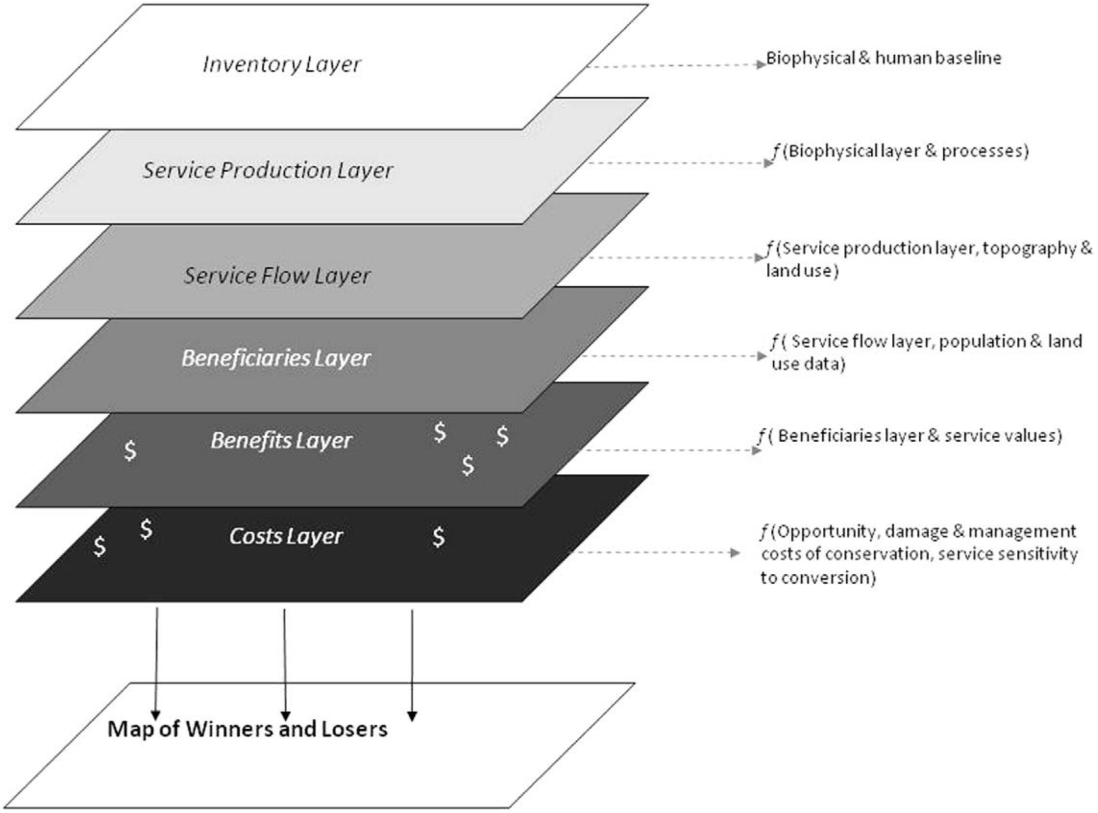

Figure 2. Series of sequential mapping exercises for assessing ecosystem services across a landscape

development strategy over the medium to long term. The uniqueness of the Eastern Arc's natural assets, and their significance for human welfare in Tanzania make this an important area for testing an ecosystem services approach and investigating the potential 'win-wins' and trade-offs between conservation and human welfare.

III Measuring, modeling, mapping

Figure 2 shows a conceptual layout for the approach we have developed for the EAM project. It is shown as a series of mapped layers, but what is not shown is the underlying data collection and modeling aspects of the approach. Here we unpack each of the layers shown in Figure 2 and discuss the data and modeling needs, some of the outcomes to date and some of the difficulties we have encountered.

1 Inventory

The first layer starts with an inventory. The ideal would be to gather all available spatially explicit data on the biophysical and social systems of interest. Data could include land-cover classes, information on climate and soils, demographic, infrastructural, and institutional variables, knowledge of resource use, etc. This information provides a backdrop for the ecosystem services that might be of interest, but also is used in developing the models that underpin other layers that characterize ecosystem services (below). For example, knowledge of land cover, road layout and forest governance might shed light on the use of forest for providing timber and might also underpin a predictive model of rates of extraction of non-timber forest products (NTFPs; Ahrends, 2005) and timber-based products (Ahrends et al.,

Table 1. Results of scoping studies on available data to map and value key ecosystem series in the Eastern Arc Mountains of Tanzania

Category	Services and Benefits	Current Data
Carbon	Carbon storage, Carbon sequestration, Climate regulation	Forest plots[1] (n= 2,300), inventory for 6 forest blocks[2]; 580km of forest disturbance transects[1]
Timber / Non Timber Forest Products	Timber, Building materials (poles, thatch), Bushmeat, Medicinal plants, Roots, Honey	As above for carbon with additional information from household surveys in > 120 villages
Water	Water flow for households, irrigation and hydropower, Flow regulation	Rainfall monthly means, river gauge data
Pollination	Forest species pollination, Agricultural pollination	Crop presence for mountain blocks, pollinator species presence
Biodiversity	Genetic storage, Existence values	Vertebrate and vascular plant species lists for all mountain blocks and most forest reserves, regional inventories of birds, reptiles, amphibians and mammals
All		Land cover, administrative and census data, infrastructure (roads, railways), soils, geology, climate data

1 = Compendium from the last 10 – 15 years
2 = from Sokoine University, Morogoro, Tanzania.

2010). In VtA, this initial stage included workshops to update existing land-cover maps, interviews of government, NGO and academic stakeholders, and using past research to identify the focal ecosystem services for the project. From stakeholder engagement and expert opinion gathered across three continents we determined that VtA, given the resources available, should focus on five categories of services and benefits – carbon, water, timber and NTFPs, pollination, and biodiversity. Each category contains a suite of services and benefits for which spatially explicit data was sought for the inventory layer (Table 1).

Wherever possible these data sets were mapped to explore spatial interactions between data sets, highlight the social context of the biophysical data and identify places where further primary data collection is necessary or where modeling needs to fill in information gaps. For example, from the Tanzania Socio-Economic Database we were able to get population statistics at a coarse district level. From the Center for International Earth Science Information Network (CIESIN, 2005) we could get a modeled surface of the population of Tanzania on a 2.5 arcminute grid. However, this layer showed people living within Nature Reserves, which we know from direct observations to be incorrect. Here, our inventory process identified a crucial layer of spatial information that needed improvement.

This step also helped to identify three focal river basins for fine-grained analysis and fieldwork: the Sigi Basin (draining the Usambara Mountains), the Ruvu Basin (draining the Uluguru Mountains), and the Kilombero Basin (draining the Udzungwa Mountains). The three basins were chosen because they are relatively well documented, have important ecosystem service flows to local and downstream users, and are the subject for ongoing policy processes. For example, the River Ruvu which drains the Uluguru Mountains supplies the capital Dar es

Salaam with a large proportion of its fresh water. Since the 1950s there has been a steady and significant decline in the baseflow of the river which is causing serious concerns for the maintenance of supply to the city (Doggart and Burgess, 2005). This decline has been linked to degradation in the forested areas of the catchment (Mbilinyi et al., 2006). In addition to these biophysical characteristics the Ruvu has a range of governance structures in place with varying ownership and management combinations including some forests co-managed by local people through Participatory Forest Management agreements (Blomley et al., 2008). While much of the data collected at this stage focused on the entire EAM study region, more detailed data sets were collected for these three study basins in order to create realistic maps and robust models, which will eventually be used to parameterize models for the whole of the EAM.

The issue of water supply to downstream users from a forested area that has few resources available for its management is also now being addressed through Payment for Environmental Services schemes (Fisher et al., 2010), which are delivering money from the city of Dar es Salaam to forest-adjacent communities to improve their land management with respect to water regulation.

2 Service production

The next layer involves understanding how, where, and at what rate ecosystem services are produced on the landscape. This requires a biophysical understanding of ecosystem processes from theory through to measurement and modeling. At the most basic level, land-cover maps can provide surface information about the types of services a landscape may provide (e.g. carbon sequestration, water supply, climate regulation). Process models and ground measurements can help to further identify, scale, and quantify services.

As an example, in the EAM we have been measuring carbon storage at different elevations and within the vegetation of different land-cover types, to develop a service production map of carbon storage. In addition a subset of plots has been monitored for three years to assess rates of carbon sequestration. One of the difficulties here is the fact that we often measure phenomena where they are most obvious – in this case, measuring carbon in forests containing many large trees. At the inventory phase we realized that the majority of previous research quantifying the carbon density of vegetation in the EAM has taken place in the high carbon storage montane forests, with little work done in woodlands, degraded forests, crop mosaics, or pure cropland. There is an equally difficult problem to overcome when building hydrological models of service production. Our early efforts to produce a map of ‘water production’ suggested the relatively dry Selous area was important for water production. This error arose because a globally available rainfall surface was extrapolating rainfall across widely spaced meteorological and river gauges, with one gauge in a high rainfall area close to the mountains, and the next in the dry centre of the Selous. The reality, not captured by the models, was a much steeper rainfall decline within a few kilometers of the mountain. Here the task of generating a first-cut map led to a series of insights about our modeling process and identified the need for further data collection. While production maps are unique to individual services, a simple overlay will indicate areas on the landscape where a bundle of services may be produced.

3 Service flow

Next, the service production maps are combined with an understanding of how services spread through the landscape and information on land use and topography to estimate where services flow from their point of production. There are a variety of spatial relationships between where ecosystem services are produced and where the benefits of those services are enjoyed, and

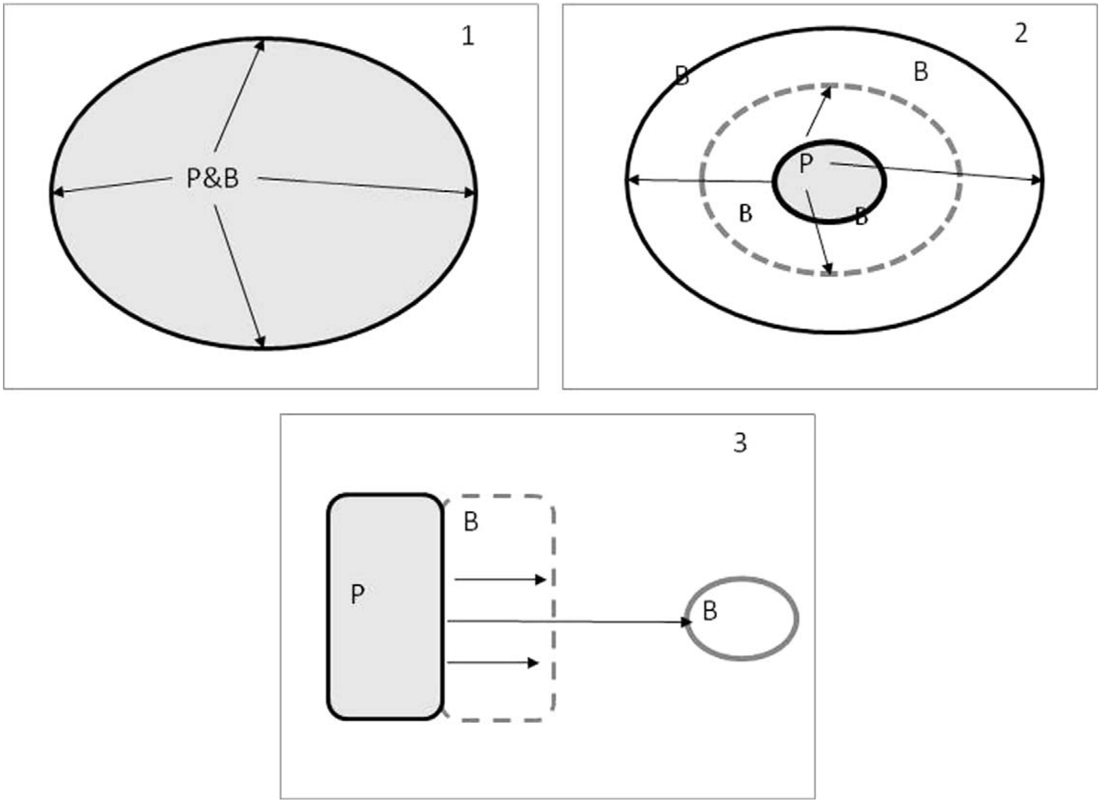

Figure 3. Possible spatial relationships between service production units (P) and service benefit units (B). In panel 1, both the service provision and benefit occur at the same location (e.g. soil formation, provision of raw materials). In panel 2 the service is provided omnidirectionally and benefits the surrounding landscape. This delivery can happen at local scales such as for pollination or pest control (dashed line) up to the global scale such as in carbon sequestration (solid line). Panel 3 demonstrates services that have specific directional benefits. For example, uphill forested areas provide water-regulation services to both local (dashed line) and regional (solid line) (based on Fisher et al., 2009).

therefore individual flow maps could be needed for each service. Some services flow globally, others may only be experienced at their point of production, and some are constrained to flow in a particular direction (Figure 3). For example, a forest can only provide water-regulation services to areas that are downstream of it. Mapping such flows requires the integration of biological processes (e.g. water uptake by plants) and physical processes (e.g. hydrological networks). One of the difficulties in this stage is that obtaining a fine-scale understanding of flows can require prohibitive amounts of data. For example, our timber production layer tells us where such a benefit is produced, and from extensive transect and disturbance data (see Table 1) we know how much ‘flows’ from our forests, but mapping exactly where the good ‘flows’ across the landscape are requires extensive fieldwork and market surveys. From pilot surveys and published NGO reports, we are building a heuristic decision model to allocate these timber flows based on the typical uses of individual species and their unit cost. For example, species with a higher end-use value are likely to travel further and to wealthier markets (e.g. larger cities).

Since an ecosystem service is inherently an anthropocentric concept, understanding these flows without linking them to actual beneficiaries only gives an example of 'potential' flows of services. Real flows materialize when beneficiaries are present.

4 Beneficiaries

In order to move from potential flows to realized flows of benefits we next need to have an understanding of where people are on the landscape and whether they utilize these flows. The concept of ecosystem services is human-focused and therefore only exists if there are human beneficiaries. If there are no human benefits (at any scale) then we are not talking about ecosystem services, but rather ecosystem processes or functioning. Therefore, connecting the flow of services to people who may consume them, i.e. translating potential service flows into benefits, is a necessary step.

Beneficiary layers are obtained from maps of service flows and land use, combined with data on the spatial distribution of people on the landscape and their use of land and resources. For example, in the average year 60% of all electricity produced in Tanzania comes from hydroelectric power from dammed EAM rivers (Ministry of Finance and Economic Affairs, 2008). The beneficiaries for this (10% of the Tanzanian population) are located in the major cities, especially Dar es Salaam, but the production areas, and those areas important for making sure the rivers flow throughout the year are likely to be well upstream from the electrified urban areas. Additionally, about half of the electricity produced (in 2007) was used for commercial and industrial ends (Ministry of Finance and Economic Affairs, 2008), offering a different suite of benefits compared to household electricity usage.

Again difficulties lie in accurately placing people on the landscape and accurately assessing their use of the service (and where necessary the timing of that use). For example, knowing how small-scale irrigators benefit from water-regulation services requires fine-grained and expensive data collection across a wide range of social and ecological contexts, and mapping how households use water for domestic uses requires extensive household surveys. Once this data is obtained, both the service flow and the beneficiaries become mappable elements.

Together the first four layers provide information about the flow of ecosystem services across a landscape to beneficiaries. In some cases translating service flows to beneficiaries will have to be an iterative process, since service provision can change across the landscape as a result of direct use. For example, removal of fresh water for irrigation in the upper Uluguru watershed of Tanzania will change the level of downstream service flow, leaving less for the downstream beneficiaries in Dar es Salaam, and therefore changing the service flow map via quantity available at different potential use points. A related key issue here is gaining an understanding of where services are mutually supportive and where there are tradeoffs among services. For example, charcoal and timber production may negatively affect water regulation in the basins, whereas carbon storage may be positively correlated with water-regulation services in a given catchment. It is likely that the models used to integrate across services will be pared-down versions of the individual service models.

5 Benefits

After understanding where services are produced, how they flow and who benefits from their flow, the next layer needed is one that gives a magnitude to the importance of that benefit. This is what we consider a value layer. Probably the most common metric of value for ecosystem service research is monetary, but alternative evaluation layers may be constructed incorporating, for example, indices of human vulnerability. For many services, the value of a given level of service provision will change across the landscape because of geographical variation in either biophysical supply or human demand. For instance, the value of clean water provision will be affected by how wealthy the beneficiaries are; what they use it for; and how scarce or abundant water is across a landscape. In the EAM our data set for charcoal prices covering 63 locations shows that prices in Dar are up to twice as high as in other urban areas, and this is not simply a reflection of transportation costs (see Edge et al., 2009). Here price is only a proxy for value, but the data does show spatial variation in value. For other services the financial value will be constant across landscapes or even globally, as in a uniform global value for carbon storage (Strassburg et al., 2009). The latter does not suggest that the value of climate regulation is homogeneous across the landscape, just the market price as its value proxy per tonne of carbon stored.

A benefit from using monetary valuation across services is that it allows for commensurability in deriving 'net' benefits and costs, by bringing each service assessed into a common metric. In Tanzania we are deriving our value layer through multiple methods. For example, we will evaluate the benefits of water provision for irrigation by a production function approach – i.e. assessing the additional productivity and value added to net crop receipts by irrigation water. The values for timber, NTFPs, and hydroelectric power services will also be imputed using market prices in a production function approach. Market and household surveys can be a direct way to get at these values, but one thing we have learned from our fieldwork is that our expectations of modeling several similar goods across such a large area were optimistic. For example, we are able to create a list of a few dozen distinct NTFPs. However, many of these are only collected in certain contexts, at certain locales, or under certain conditions (e.g. rainy season). In response to our findings from the market and household surveys we are therefore modeling only the most commonly collected NTFPs – poles, firewood, mushrooms, charcoal, thatch, as well as trying to bundle some wild fruits and vegetables. These are products whose production we can attempt to model and to which we can also attribute values, as well as examine potential substitutes in the market place. Therefore we exclude medicinal herbs, honey, fibers for baskets, rope, and fodder collection from our modeling.

The benefits of biodiversity conservation also present a complex valuation problem, including accounting for the differences between 'local' people and their value preferences and residents in international 'donor' countries (Hanley et al., 2003; Horton et al., 2003). In VtA our objective was to estimate the willingness to pay of UK (donor country) residents for conserving wildlife in the EAM, using a split sample survey design (Morse-Jones et al., 2010). A choice experiment method was used to present respondents with a series of questions describing the possible outcome for wildlife if current development pressure trends continue and if conservation measures are implemented. In the choice experiment, respondents were asked to choose their most preferred option in each question. The options were described in terms of three attributes: (1) the number of unique species saved; (2) the number of non-unique species saved; and (3) the donation by the household to enable outcomes to be achieved. The levels for the donation were based on a literature review and pretesting. By varying the attribute levels across the options and modeling how this affects choices we were able to estimate willingness to pay for total changes in wildlife conservation, as well as for changes in the individual attributes. The experiment suggested that UK residents were willing to pay on average £53 (2008 GBP) per household per annum for conservation efforts in the EAM (Morse-Jones et al., 2010).

6 Costs

Benefit values are only one side of the coin. In order to make robust policy recommendations we need to have an understanding of both the benefits of a functioning ecological landscape as well as the costs of providing that landscape. The costs of conserving landscapes for ecosystem service provision include not just the direct management costs of interventions (such as salaries for park guards) but also the opportunity costs for local stakeholders (i.e. their net benefits foregone as a result of conservation), implementation and transaction costs of a conservation intervention, possible acquisition costs, and any damage costs that might be incurred (Naidoo and Ricketts, 2006) – in our case crop damage would most likely be caused by vervet monkeys, baboons, and bushpigs. In the EAM, the opportunity costs of conservation are found by examining the profitability of the foregone farming and fuel collection opportunities. For example, in some districts of the EAM up to 95% of the people are either employed in agriculture or are subsistence farmers, meaning that any further designation of restricted land use could directly affect opportunities for agricultural expansion. We have found that, on the district scale, the agricultural opportunity costs of conservation vary widely (NPV $400/ha–$8000/ha), and that by including the profit foregone from charcoal production (in the case of a woodland being converted first for charcoal and then agricultural use) the opportunity cost can increase by 12–167% (B. Fisher, unpublished data). An extensive field survey showed that variation in yield between farmers and across years makes it difficult to model opportunity costs at a fine scale using data from household surveys, which means these costs will likely be modeled at a coarser scale such as the ward level (i.e. several villages).

Another difficulty we have faced with modeling costs is the availability of data regarding the management and implementation costs of conservation. In some contexts this type of information might be readily available, but in our EAM project it requires a concerted effort to collate data from online records, government reports in scattered locations, and interviews with government staff. The range of different governance types which are used to manage the landscape also make it difficult as understanding the costs needed to manage a central government-administered Nature Reserve will require different data-acquisition strategies than, say, those bearing on the management of a village-based forest reserve.

Both the valuation and cost steps require interaction with the development of scenarios (see below) in order to construct some form of ‘marginal’ values. For example, the marginal benefits of any given ecosystem service and the costs for securing the delivery of that service are functions of the difference between two states of the world – perhaps the current state and one where conservation schemes are initiated. The development of scenarios and their integration with the modeling and mapping exercises is explained in more detail below.

7 Mapping winners and losers

The advantage of measuring costs and benefits in the same monetary units is that you can combine the benefits value layer and the cost layer into one map. The result is a map with clearly demarcated areas of net gains and net losses. For example, if a current forest reserve involves high locally incurred costs (e.g. opportunity or damage costs) and limited local benefits (e.g. through NTFP provision), but delivers significant benefits (such as water flow regulation) at low cost (e.g. limited management cost) to people living in Dar es Salaam, then the map may show net losses nearby and net gains further away. An aggregated non-spatial summary of total costs compared to total benefits would not reveal this spatial variation, and would therefore not indicate where cost-benefit differentials are the smallest. Yet understanding such asymmetries is evidently crucial for the design of equitable policy interventions. In the EAM, CARE and the World Wildlife Fund are facilitating project work on the Ruvu River that aims to link the beneficiaries of the water flowing from the Uluguru Mountains (mainly in Dar es Salaam) to those living and managing the land in these mountains. The intention is to ensure that land-use practices in the mountains help maintain water quality and that major water users pay the communities for their efforts and for foregone opportunities of forest conversion (Fisher et al., 2010). Providing maps of where these benefits are being produced and the relative costs of producing them will aid in targeting specific subbasins, but also indicate the magnitude of compensation required.

IV Scenario building

The above steps all involve modeling phenomena that are dynamic and will change under different possible futures. Exploring the possible consequences of such change is vital if an understanding of ecosystem services is to be useful to decision-makers. They need to know not just about the gross values of services delivered from a particular area but about the likely net differences in value (incorporating costs as well as benefits) arising from the decision confronting them (say, to sanction a forest to be converted or not). Understanding these values spatially can help to understand how to optimize a landscape for a given goal (e.g. net benefit return), aid in comparing alternative policy impacts, or highlight potential future changes driven by different potential futures.

Key drivers of resulting differences in service values include land-use change, demographic shifts, changes in patterns of demand, technological innovations and climate change. To explore the impact of such changes on human welfare requires scenario building. Typically, scenarios are presented as 'storylines' which are internally consistent and offer plausible future possibilities (Gallopin et al., 1997; MA, 2005; Peterson et al., 2003; Raskin, 2005). Rather than representing a specific prediction, each scenario should be thought of as a description of a possible future which has plausibility given the knowledge and assumptions on which it is based. When done thoroughly, scenarios can guide policies towards specific end goals such as increasing human welfare or equity (Turner, 2005). Scenario building has become an important part of multidisciplinary research being widely used in land-use planning (Verburg et al., 2006; Xiang and Clarke, 2003), climate change analysis (IPCC, 2007) and conservation planning (Sala et al., 2000), and, increasingly, in ecosystem service assessments (Castella et al., 2005; MA, 2005; Walz et al., 2007).

In relation to our mapping approach, future scenarios would change each of the layers in Figure 2. For example, a future with an increase in road infrastructure would alter the base inventory layer (and any layers that are in turn informed by it); while a future with more forest conservation would affect the production, flow, beneficiaries, benefits, and costs layers, and therefore the resultant map of winners and losers.

For VtA, we developed two socio-economic scenarios with Tanzanian stakeholders in a series of participatory workshops (see Swetnam et al., 2011). Both scenarios relate to the year 2025 (Table 2). Matazamio Mazuri (MM) means 'hopeful expectations' in Kiswahili and represents a future where Tanzania fully meets its stated policy goals on poverty alleviation and natural resource management, but still reflects the reality of a population growth and economic pressures. Kama Kawaida (KK) means 'as usual' in Kiswahili and corresponds to a business-as-usual scenario where a growing population combined with ongoing resource exploitation leads to continued environmental degradation and steady-to-declining family income.

Our scenario-building process continued with more formal descriptions of how the storylines impact on different sectors (agriculture, water supply, tourism, forestry, and population). The

Table 2. A comparison of the key socio-economic drivers embedded in the two scenarios used in the land-cover modeling: Matazamio Mazuri ('hopeful expectations') and Kama Kawaida ('business-as-usual')

Descriptor	Matazamio Mazuri (2025)	Kama Kawaida (2025)
GDP growth	6%	5%
GDP per capita	$1500	$1100
Growth sectors	Tourism, Mining and Agriculture	Agriculture (area not productivity)
Population growth	2%	3%
Population by 2025	55 million	60 million
Population with access to electricity	40%	20%
Energy sources	Gas, coal, Hydro-electric Power Biomass (firewood and charcoal) main source for cooking but demand falling through technology interventions (stoves / waste residue fuels)	Gas, some coal and HEP. Biomass remains the main energy source.
Agricultural sector	Remains largest employer and largest component of GDP. Marketing, processing and improved transportation increases productivity. Some expansion of irrigated agriculture. Livestock production increases.	Remains largest employer and largest component of GDP. Productivity remains low with irrigated agriculture rare. Small-scale farming dominates with much work still done by hand and hoe.
% area under medium-large-scale farming	Doubles to 30%	Remains at 15%
Global financing	International payments for Carbon (through REDD) and PES schemes grow.	Payment schemes fail to be implemented in any significant manner.
Protected Areas	Increasingly well monitored and managed. Encroachment and illegal timber harvesting is arrested. Integrated catchment management is improving.	Little capacity for monitoring and management. Encroachment and illegal timber harvesting continues in reserves. Small-scale mining increases in the mountains.

sectoral impacts were then translated down to ordinal-level impacts on specific human-environment interactions (e.g. 'large increase in area under agriculture'). Finally, further discussion established a series of rules for translating these ordinal scores into changes in our mapped surfaces (Swetnam et al., 2011). So in the case of a large expansion in agriculture we needed a rule for establishing the location and magnitude of this expansion, and so considered that agriculture expands in areas abutting existing agricultural land until the threshold prescribed in the storyline is met (e.g. 10% increase in agriculture). Once such mapped outputs have been generated they can then be used as revised inputs to the layers in Figure 2, thereby generating descriptions of the plausible gains and losses that may be incurred by specific future courses of action.

V Illustrative example of the mapping approach

Here we provide a brief stylized example of how the mapping approach can help provide insights

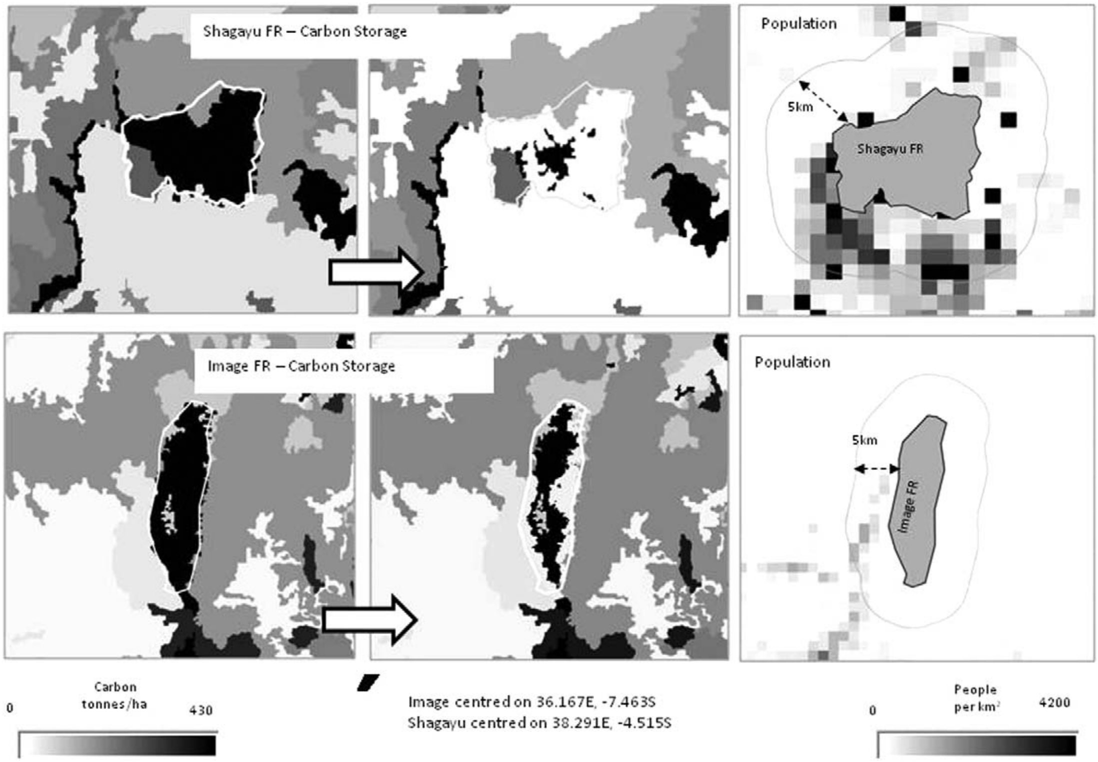

Figure 4. Changes in carbon storage for the Shagayu and Image reserves when moving from montane forests to agricultural land (left). Forest reserve boundaries and village locations within a 5 km buffer (right).

for policy and management decisions based on some preliminary results from our project. We focus on the carbon stored in two Forest Reserves, Shagayu and Image (both ~ 80 km^2 in size), and examine the relative costs and benefits of the conversion of these forests by expanding subsistence agriculture.

Starting with the inventory layer, we map population around the reserve, the reserve boundaries, and land cover within and surrounding the reserves (Figure 4). The production layer considered here is simply the carbon stored in each landscape as in this example we are only concerned with a single ecosystem service (Shagayu: mean 325 tC/ha; Image: mean 277 tC/ha). Likewise, for this initial test we generate our production layer simply using mean values from the literature of carbon storage in each land-use type, for each of four pools: above ground, below ground, soil, and dead matter. The flow and beneficiary layers are unmapped as the benefits of carbon storage, i.e. climate regulation from this carbon not entering the atmosphere, are assumed to accrue globally regardless of where the carbon is stored (because CO_2 is a well-mixed gas in the atmosphere). The value layer could be derived using a range of existing monetary values for carbon: voluntary carbon markets ($\sim$\$5/tCO_{2eq}), compliance markets such as the European Trading Scheme ($\sim$\$18/tCO_{2eq}), and damage cost avoided estimates ($\sim$\$15–\$50/tCO_{2eq}) (Tol, 2005) that are all readily available and defensible under differing assumptions. For our example, however, we will forego appending a value to the carbon and discuss the important underlying issues further below.

For the cost layer we created an opportunity cost based on the net rents from the top five

Table 3. Costs and Benefits of conversion of forest to agriculture in the Shagayu and Image Forest Reserves

Forest Reserve	Estimate of stored carbon (mil. tonnes)	Carbon lost if forest is replaced by agriculture (mil. tonnes CO_{2e})	Opportunity cost of conservation (charcoal and agriculture)	Management and implementation costs of conservation	Necessary carbon price to offset costs*	Number of people living within 5km
Shagayu	2.6	5.1	\$ 10.3 million	\$ 233 thous.	\$ 2.06/tCO_2	35793
Image	2.5	3.3	\$ 5.67 million	\$ 162 thous.	\$ 1.70/tCO_2	637

*Reported in \$/tCO_2 where $1\ tCO_2 = 1/3.667\ tC$

crops grown in the Lushoto and Kilolo districts where the reserves occur (Shagayu and Image, respectively) based on the average crop yield and regional market price (*NPVs 30 years r=10%*). We also added the foregone benefits of charcoal production specific to the forests in these districts that are converted under our scenario. These costs are just an approximation of the opportunity costs at these forest reserves because, for one, they are based on district values. We also added management and implementation costs for managing a carbon-offset project for the projected converted areas (proxy for managing the forest reserves) (Borner and Wunder, 2008). Specifically, the opportunity cost was calculated as:

$$O_x = \sum_i^1 (y_{ix}\, a_{ix}\, p_i) - C + .34Gn + M$$

where O_x is the cost of conservation in x; a_{ix} is the area planted with crop i in x (ha); y_{ix} is the yield of crop i in x in tonnes/ha (National Bureau of Statistics et al., 2007); P_i is the price of crop i from regional price data in USD/tonne (FAO's PriceStat database); and C is the cost of inputs including cost of seeds, transportation, land, labor, and fertilizer (B. Fisher, unpublished data; National Bureau of Statistics et al., 2007).

G is the above-ground biomass in a given hectare (in kg), and .34 represents a conversion of biomass to charcoal based on kiln efficiencies and published fieldwork and n is the profit from charcoal production (\$/kg) (Malimbwi et al., 2007; Van Beukering et al., 2007). M is the proxy measure for management and implementation costs (Borner and Wunder, 2008).

When we add up the costs of conserving the forest reserves (countering the conversion scenario) we get values of \$10.6 million (\$2200/ha) and \$5.6 million (\$1660/ha) for the Shagayu and Image reserves, respectively. In the conversion scenario, from our modeling, we know that the Shagayu and Image Forest Reserves lose 1.4 and 0.9 million tonnes of carbon, respectively. Here, rather than applying a value to each tonne of carbon, we can simply calculate the necessary price of carbon in order to offset the opportunity and management costs of maintaining the two forest reserves, based on this stylized example. The breakeven carbon price for the Shagayu Reserve is \$2.06/tCO_2, meaning that a carbon price set at that level could compensate the costs incurred in continuing to conserve that landscape. Similarly, the breakeven carbon price for the Image Forest Reserve is \$1.70/tCO_2 (see Table 3). The knock-on policy question is whether these carbon payments can be realized.

This example looks at just one benefit (carbon storage), two costs (opportunity and management costs), and one scenario. A more comprehensive assessment of the conversion costs and benefits of these two forest reserves would incorporate a fuller suite of ecosystem services including water regulation, pollination, and other NTFPs. Additional costs not accounted for here include soil depletion, damage costs, and some measurement relating to how conversion or conservation might affect market prices of agricultural and timber products. However, even this simple example illustrates our approach, and provides insight on the partial costs and benefits of conservation versus conversion. The example also points out the spatial aspect of production, costs, and benefits as they differ greatly between the forest reserves. Further, these reserves were selected because they are similar in size, but set in contrasting locations. The Shagayu occurs in the heavily populated Usambara Mountains, while the Image is located in the sparsely populated Udzungwa Mountains. This distinction is critical if we were not concerned simply with the value of carbon, but rather with how many people would be impacted by foreclosing their option to convert forest into agriculture. In this case the stakeholders who benefit from carbon storage are largely global, while those paying the greatest share of the costs are local. Table 3 shows that there are an estimated 35,793 people living within 5 km of the Shagayu Reserve, but fewer than 700 people within 5 km of the Image Reserve. If the Tanzania Government, or a carbon-buying institution, had to decide which forest to conserve they could be faced with a choice of foreclosing the opportunities of some percentage of the 35,000 people or some percentage of the 700 people. The latter might be more plausible politically and potentially more easily compensated. Alternatively, they could see these population disparities as pressures and an argument that by protecting the Shagayu they are demonstrating additional carbon saved in the face of a greater conversion threat.

The simple example of our approach allows us to consider multiple policy or management options in the face of a changing landscape, but in the future it will enable such decision-making on an analysis of several services, multiple costs and a suite of scenarios, delivering an added depth of information to the decision-making process.

VI Conclusion

In the past few years we have learned much about how ecosystem service research can best inform decision-making. Key lessons include the importance of integrating cost data, in addition to benefit data (Ando et al., 1998; Naidoo and Ricketts, 2006); making spatially explicit assessments at both ecologically and policy-relevant scales (Chan et al., 2006; Rouget et al., 2006); and employing contrasting scenarios that are meaningful to decision-makers (Balmford et al., 2008). Our approach described here incorporates these insights and delivers policy-relevant information in an easily accessible way. There are obvious difficulties in undertaking this approach, but by highlighting those which we have encountered in our own case-study work, we have also been able to suggest some routes to overcoming these impediments.

Our approach was designed to address the impacts of different policy options on ecosystem services and their role in providing human well-being. It is intimately concerned with equity issues, in that a key output is a map of the relative winners and losers of various different future scenarios and policies. We also see it as a general approach, which can be applied at various scales and with varied levels of input detail. Of course there remain several key challenges within our project and the larger ecosystem service research agenda. For example, how do we incorporate the importance to human welfare of those services which conventional economic valuation fails to meaningfully express? What are the transaction costs of applying such a research program? How can such an approach be undertaken in contexts where data and funding are limited and institutions weak? How do we understand service flows and values that change spatially and temporally over short timescales, e.g. seasonal variations, migrations, fluctuating stocks? How can we incorporate ecosystem services and their valuation into climate change models that include representations of the land surface (Doherty et al., 2010)? This set of questions represents only a fraction of those that remain for more robust ecosystem service analysis. While these challenges may seem significant, the importance of delivering accurate and timely information on the role well-functioning ecosystems play in human welfare will continue to grow.

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