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Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling

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ABSTRACT

We present a GIS method to interpret qualitatively expressed socio-economic scenarios in quantitative map-based terms. (i) We built scenarios using local stakeholders and experts to define how major land cover classes may change under different sets of drivers; (ii) we formalised these as spatially explicit rules, for example agriculture can only occur on certain soil types; (iii) we created a future land cover map which can then be used to model ecosystem services. We illustrate this for carbon storage in the Eastern Arc Mountains of Tanzania using two scenarios: the first based on sustainable development, the second based on ‘business as usual’ with continued forest–woodland degradation and poor protection of existing forest reserves. Between 2000 and 2025 4% of carbon stocks were lost under the first scenario compared to a loss of 41% of carbon stocks under the second scenario. Quantifying the impacts of differing future scenarios using the method we document here will be important if payments for ecosystem services are to be used to change policy in order to maintain critical ecosystem services.

1. Introduction

It is widely accepted that intact ecosystems provide an array of services – from immediate and tangible benefits such as water flow regulation and provision of harvested goods through to biodiversity preservation and climate stabilisation via carbon storage in vegetation and soils (Costanza et al., 1997; Daily, 1997; de Groot et al., 2002). Although there remains much theoretical debate about the definition of such services and approaches to their valuation (Ruhl et al., 2007; Wallace, 2007; Costanza, 2008; Boyd and Banzhaf, 2007; Fisher et al., 2009) one common thread is clear: ecosystem service production and flow is spatially explicit and temporally dependent. It matters not only how much of a service is produced, but also when and where, so any economic values we assign to these services will therefore also vary across space and time.

The spatially variable nature of service generation and flow means that mapping and modelling of ecosystem services for planning purposes is becoming increasingly important (Naidoo and Ricketts, 2006; Egoh et al., 2008). Datasets have become more sophisticated, shifting from a simple benefits-transfer approach (Zhao et al., 2004; Troy and Wilson, 2006) to values derived from biophysical and economic models (Eade and Moran, 1996; Bateman et al., 1999; Mallawaarachchi et al., 1996; Soares-Filho et al., 2004, 2006). Typically, the links between models of different services are made through synoptic land cover datasets. The distribution and value of services can be expressed spatially in this way and changes modelled by altering land cover patterns and extent. Sometimes these land cover driven futures operate over large regions with notable examples from the USA including ICLUS which was developed by the Environmental Protection Agency (US EPA, 2009) drawing on the earlier work of Theobald (2001, 2005), and

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the US Geological Service supported CBLCM and SLEUTH (see Claggett et al., 2004 for a review).

Decisions based simply on gross estimates of service values will however, be of limited use. Instead information is needed about policy-induced changes to services and the corresponding values attributed to them. Such decision making can be helped by the use of scenarios – internally consistent and realistic narratives describing potential future states (Peterson et al., 2003). Typically, these are presented as 'storylines' which are constructed using existing conditions and processes but also incorporate likely future changes in important drivers, these storylines are internally consistent and viewed as physically realistic future possibilities (Gallopin et al., 1997; Raskin, 2005). Rather than representing a specific prediction each scenario should be thought of as a description of a possible future, albeit one which is plausible given the knowledge on which they are based. Scenarios are widely used in land use planning (Xiang and Clarke, 2003; Verburg et al., 2006), climate change analysis (IPCC, 2007) and conservation planning (Osvaldo et al., 2000) and, increasingly, in ecosystem service assessment (Castella et al., 2005; Millennium Ecosystem Assessment, 2005; Walz et al., 2007).

The process of scenario-building often involves a stakeholder group which develops qualitative storylines of expected change (termed 'participatory scenario-building', Alcamo, 2009). Such approaches have the potential advantage of using a wide base of local knowledge and building broad ownership of the process and the ensuing results. But participatory approaches are time-consuming in countries where contributors are geographically dispersed, and there can sometimes be both practical and institutional barriers to sustained participation. In addition, the ideas generated by participatory scenario-building can be hard to parameterise. For example, in a recent study from Switzerland a rigorous participatory exercise relating to landscape change around the skiing resort of Davos was undertaken (Walz et al., 2007; Grêt-Regamy et al., 2008). Many interesting outputs were documented but attempts by researchers to integrate outputs into the formal modelling process were unsuccessful and resulted in them abandoning this approach and taking a "*more intuitive, concept-driven approach to scenario development*..." (Walz et al., 2007, p. 120).

These difficulties can be overcome and here we move from participatory exercises in developing future scenarios to a formal modelling framework, and apply it to a test case of carbon storage in four mountain blocks of the Eastern Arc Mountains, Tanzania. This is a useful case-study area, firstly, Tanzanian policy-makers have highlighted carbon storage as being of topical policy interest, because the concept of Reduced Emissions from Deforestation and Degradation (REDD) is being considered for inclusion under the UN Framework Convention on Climate Change and Tanzania is a pilot REDD country (Miles and Kapos, 2008). Secondly, this is one of a number of ecosystem services being studied in the same area, so eventually this method will be used to consider the trade-offs and synergies between different ecosystem services (Burgess et al., 2009).

This paper is in three parts. Firstly, we discuss the scenario-building process within the context of the Tanzanian study area and describe our method for extracting quantitative information from qualitative narratives formulated to describe two socio-economic scenarios of change. Secondly, we provide spatial representations of these two scenarios as alternative land cover projections mapped for eastern Tanzania. Thirdly, to illustrate the consequences of these possible land cover changes for a particular service, we use these maps as inputs to a simple carbon storage model and quantify how these alternative scenarios influence the amount, location and value of carbon stored in our focal study area.

2. Method

2.1. Study area

Our study is both regional (covering most of eastern Tanzania) and local (covering four of the mountain blocks which make up the northern part of the Eastern Arc Mountains). Our land cover maps were developed for the wider region, whilst the carbon storage model was applied to the local study area.

The study region covers nearly 340,000 km^2 (Fig. 1). It is a mixed landscape comprising a patchwork of bushland, scrub, swamps, mangroves, deciduous and open woodland (miombo), wetlands and evergreen tropical forests, mixed with small-scale cultivation and settlements. Parts of the coastal strip are densely populated and include Tanzania's largest and fastest growing city, Dar es Salaam. Topographically, the study area can be split broadly into the eastern coastal plains (0–350 m) and the western highlands and plateaus rising to over 2000 m. In addition, the coastal zone and mountains are wetter (1000–2200 mm yr^{-1}) while the interior zones are drier with some areas receiving as little as 370 mm yr^{-1}.

Running almost north to south through this region are the Eastern Arc Mountains (EAM), 13 separate mountain blocks covering a combined area of over 35,000 km^2. These mountains are important centres of biodiversity with high levels of species endemism both for plants and animals and recognised as globally important conservation areas (Lovett and Wasser, 1993; Mittermeier et al., 1998, 1999, 2004; Stattersfield et al., 1998; Burgess et al., 2007; Menegon et al., 2008; Myers et al., 2000). Approximately 22% of the total area of the EAMs has some state restrictions on permitted activities (forest reserves, nature reserves or national parks).

Besides their value for biodiversity, the EAM provide many ecosystem services. These include services provided to the local inhabitants of the mountain settlements, such as the provision of energy (firewood), building materials (poles and thatch) and food (fruit, tubers, honey, bushmeat), as well as services provided to those distant from the mountains themselves. These include the regulation of water flows from the EAM to downstream agricultural areas and the major population centres of the coast (where the water is used for hydro-electric power generation as well as drinking and industry) and the provision of wood for charcoal which fuels the majority of urban households in Tanzania. At a global level the EAM contribute to climate regulation through the storage of carbon.

2.2. Data

The key dataset used in this paper is a land cover map derived from a 1997 survey by Hunting Technical Services (Hunting Technical Services, 1997). The original has been updated by local experts and tropical biologists and now contains 30 land cover classes at a resolution of 100 m and has been given a nominal date of 2000. More recent land cover products including Globcover (Bartolomé and Belward, 2005) and Africover (FAO, 2008) overestimate the forest and woodland classes in the study region and were felt to be less representative than the earlier but Tanzanian-specific Hunting dataset. The land cover dataset was supplemented by the following spatial datasets:

- Elevation and slope – derived from the USGS Shuttle Topography Radar Mission (STRM) (Farr et al., 2007);
- Protected area outlines – derived from the latest version of the World Database of Protected Areas (WDPA, 2009);
- Road and rail networks – digitised from the available 1:50,000 topographic maps;
- Settlements – villages digitised from the 1:50,000 maps;

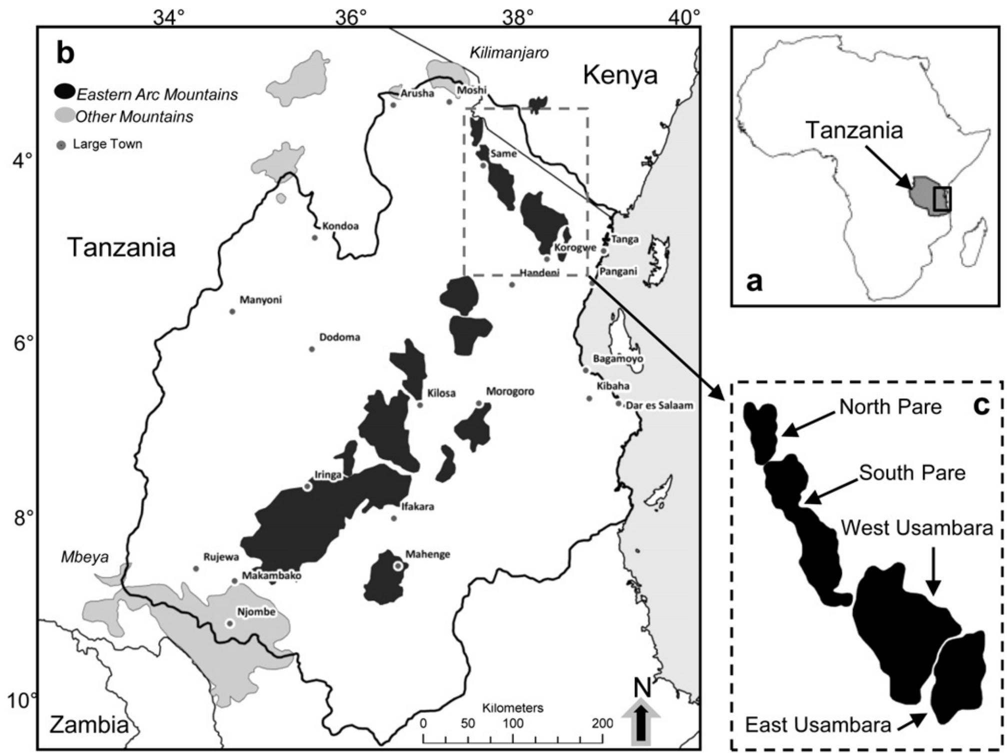

Fig. 1. Location of the study in Africa (a) and in Eastern Tanzania (b) with the regional study area outlined in black encompassing the catchments of the 13 blocks which make up the Eastern Arc Mountain chain in Tanzania. The four blocks for which carbon values are calculated are shown in (c). The wider study area shown in panel (b) covers 338,588 km^2.

- Soils – extracted from the Harmonized World Soil Database (FAO, 2009).

All datasets were projected into UTM 37 South using a WGS1984 geographic coordinate system with the raster datasets additionally re-sampled to a common spatial resolution of a 100 m grid.

2.3. Building the socio-economic scenarios

Our two socio-economic scenarios relate to the year 2025 and were developed with Tanzanian stakeholders in a series of participatory workshops and interviews (Table 1). There were five sequential steps in this part of the process:

1) A literature review of scenario generation and implementation to assess current practice. This was complemented by review of all relevant Tanzanian policy and strategy papers in the socio-economic sectors of relevance (water, energy, agriculture, etc., see Table S1 for further information and links).
2) A first round of key informant interviews to clarify current trends in resource use in the EAM and to develop a shared policy vision of what Tanzania would look like in 2025.
3) An initial workshop with stakeholders to clarify the purpose and scope of the scenarios and to outline the main interactions between the economic sectors which feed into them. The outputs of stages 1–3 were drafted and the outline narratives of the scenarios were circulated to participants for comment.
4) This was followed by a second round of key informant interviews to present the draft scenarios. Feedback from these discussions was then used to focus and refine the scenarios further.
5) A second workshop then translated the qualitative storylines into quantitative rules to model landscape change.

Our first workshop defined the links between socio-economic drivers of change in the EAM and their subsequent impact on the ecosystem services that the EAM provide to the people of Tanzania. Each economic sector was considered in turn and the participants discussed the current state of the sector and any expected or possible changes to that sector by 2025. Both opportunities for growth and impediments to change were explicitly considered at this point. Participants considered the current trajectories of change in each sector from the present up to 2025 and were asked to list any current policy interventions which might drive these changes. Finally, the interactions between sectors were explicitly considered with respect to ecosystem services of relevance to our research programme, including fuelwood collection, charcoal production and water availability. So for example, how would projected improvements to the transport infrastructure affect the extraction of non-timber forest products (such as firewood and charcoal) in the EAM? The stakeholder interviews and the workshop discussions provided the starting point from which the narrative scenarios emerged. At this stage they were purely qualitative but rooted firmly in key facts about the socio-economic drivers of change (Table S1). When these narratives were presented to our key stakeholders in a second round of interviews, those involved in the Tanzanian policy process advised us to focus on two scenarios of most immediate relevance: a business-as-usual situation and a second where poverty reduction strategies and environmental improvements are implemented.

In our second workshop we presented these two scenarios which were named Matazamio Mazuri (MM) and Kama Kawaida (KK). Their Swahili names reflect the general ethos described by their descriptive narratives. Matazamio Mazuri means ‘hopeful expectations’ and represents a future where Tanzania begins to meet its stated policy goals on poverty alleviation and natural resource management but still reflects the reality of a growing population and economic pressures. Kama Kawaida means ‘as

Table 1
A comparison of the key socio-economic drivers embedded in the two scenarios used in the land cover modelling: Matazamio Mazuri ("optimistic") and Kama Kawaida ("business-as- usual") as constructed for the Eastern Arc Mountain region of Tanzania. See Table S1 for further details.

Descriptor	Matazamio Mazuri (2025)	Kama Kawaida (2025)
GDP[a]	$1500 (growth rate of 6% per annum)	$1100 (growth rate of 5% per annum)
Growth sectors	Tourism, Mining, Agriculture	Agriculture
Population	55 million (growth rate of 2% per annum)	60 million (growth rate of 3% per annum)
Population with access to electricity	40%	20%
Energy sources	Gas, coal, Hydro-electric power (HEP) increasingly important for electricity generation. 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. Agricultural area under medium-large scale farming doubles to 30%.	Remains largest employer and largest component of GDP. Productivity remains low and irrigated agriculture rare. Small-scale farming dominates with much work still done by hand and hoe. Agricultural area under medium-large scale 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 are arrested. Integrated catchment management is improving.	Little capacity for monitoring and management. Encroachment and illegal timber harvesting continue in reserves. Small-scale mining increases in the mountains.

[a] Gross Domestic Product based on purchasing power parity (PPP) per capita GDP.

usual' 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. The first step in moving from qualitative storylines to quantitative rules was to consider the direction and magnitude of change in each economic sector by 2025. For example, the energy sector: one policy goal of the Tanzanian government is to improve electricity generation through greater investment in Hydro-Electric Power and fossil fuel sources. In particular, there is a need to increase the role that fossil fuel power stations have in mitigating the impacts of fluctuating rainfall on electricity production. Participants reflected on this potential change in the energy sector and considered how this would affect fuelwood extraction, charcoal consumption and agricultural expansion. Participants then rated the magnitude of these effects; increasing electricity generation might lead to reduced fuelwood extraction, reduced charcoal production but no effect on agriculture. We generated impact tables to prescribe how anticipated changes might translate into trends in land transformation such as 'agriculture increases'. The changes in five major sectors (energy, formal economy, agriculture, forestry and population) were considered with respect to ten parameters which measured human-environment interactions (e.g. agricultural expansion) in the EAM (B. Fisher, unpublished data).

The participants then considered how these trends could impact on land cover across the region and helped construct simple diagrams which capture the current state and the possible future of land cover in 2025 (Fig. 2 and Fig. S1). The baseline land cover map for 2000 has 30 classes between which there are 900 possible combinations of change; to simplify this for discussion these 30 were grouped into seven: woodland, mixed with crops, grassland, bushland, agriculture, forest and other (Table 2). The workshop participants then concentrated on the main land transformations of relevance to each scenario which are indicated in Fig. 2 by the dashed arrows between 2000 and 2025. A number of assumptions are implicit in this figure including:

- Once land is cultivated it remains as such.
- There is an implicit gradient of land use intensity: agricultural land is used more intensively than areas classed as mixed with crops which represent heterogeneous landscapes of subsistence farming interspersed through bushland, grassland or woodland.
- There is no significant change in the 'other' category. This category does include urban areas and it is recognised that urban growth and rural to urban migration are significant land transformation processes in parts of Tanzania but their current impact in terms of total land area is relatively local within the study region.
- Population is increasing rapidly and according to recent predictions could reach 67 million by 2025 (United Nations, 2008). Although there have been some increases in crop production since 1979, these gains have easily been outstripped by population growth resulting in a drop in total per capita food production (EarthTrends, 2003). The relatively large increase in agricultural land (from 8 to 10% for MM and from 8 to 12% for KK) is driven by this change.

The actual values used to determine the modelled changes in land cover are not intended to be fixed or prescriptive and the flow diagrams are only intended to capture the key changes. At present they represent one interpretation of the MM and the KK scenarios and further discussions will inevitably lead to different combinations of values between years. Those changes shown in Fig. 2 (and Fig. S1) represent a first attempt to quantify the narratives which are summarised in Table 1 and are used here to illustrate the spatial modelling method.

2.4. From scenarios to maps

In order to use our narrative-based scenarios as a basis for quantifying the consequences of alternative development trajectories for ecosystem services we next needed to transform them into maps representing possible end-points if the trends described by the scenarios were realised. Our GIS model used a two-step process which started with generous Boolean rules to act as the first filter followed by a grading process to identify relative preferences for change.

For each land cover group a series of rules were constructed to govern where changes could occur. These rules were derived using a process which started with the biophysical (so changes determined by factors such as soil, climate or accessibility) then

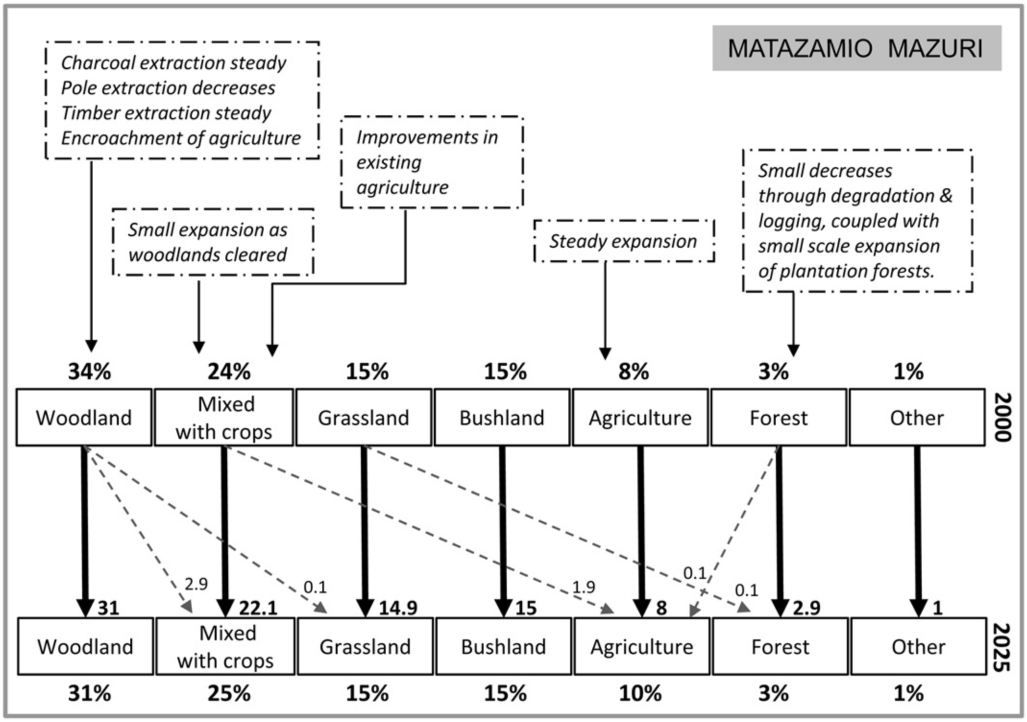

Fig. 2. Expected land cover transitions under the Matazamio Mazuri scenario with the top line of boxes showing the distribution of the main land cover groups in 2000 and the bottom the estimated situation in 2025. Bold arrows between classes show those components which have remained unchanged, dashed arrows indicate fluxes between classes.

narrowed by location (so changes targeted to particular administrative regions or districts) and then refined by type. Initially, these rules were expressed in general terms such as 'Where the climate is suitable' or 'Near to a road' but were gradually refined and eventually quantified with ancillary data and reference to existing literature. So for example, 'where the climate is suitable' becomes 'where the annual rainfall is at least 800 mm yr^{-1}' and 'near to a road' becomes 'within 5 km of a tarmac or gravel road which is passable by motorised traffic all year round'. This process was followed through for all the six main types of land cover and the rules governing which areas can change are summarised in Table 3.

These rules are the same for both scenarios, with one major exception. Under MM, all of the existing protected areas from the National Parks down to village forest reserves are excluded from change (so their conservation designation acts as a constraint to land cover change). In contrast, the pessimistic KK scenario loosens this constraint and only preserves the higher status protected areas such as National Parks, Nature Reserves and Game Reserves, while the forest reserves and community forests are opened up to land transformation. It can be seen from the detail and number of rules associated with agricultural expansion, that the workshop participants felt that this would be the primary driver of land cover change in the region and as a consequence they afforded it the most attention.

Once the rules were quantified, each could then be expressed as a conditional statement which was applied to the relevant digital datasets to produce a series of Boolean grids (Fig. 3). These individual outputs were then combined to find those cells which meet

Table 2
Land cover group totals and class composition for the year 2000, and two alternative policy scenarios for 2025. Total study area is 338,588 km^2.

Land cover group	Land cover class	% of study area		
		Present	Matazamio Mazuri 2025	Kama Kawaida 2025
Woodland	Closed Woodland Mangroves Open Woodland (miombo)	34	31	30
Mixed with crops	Bush with scattered crops Grass with scattered crops Woodland with scattered crops	24	25	26
Grassland	Grass	15	15	15
Bushland	Bush	15	15	15
Agriculture	Cultivation Plantation agriculture (tea, rubber, rice, sugarcane, other monocrops)	8	10	12
Forests	Forest Mosaic, Lowland Forests Sub-montane Forests, Montane Forests, Upper-montane Forests, Plantation Forest	3	3	1
Other	Bare Soils, Inland Water, Ice/Snow, Permanent Swamp, Rock Outcrops, Urban	1	1	1

Table 3
A comparison of the rules derived from the qualitative narratives of the stakeholder workshops and their subsequent quantitative expression for use in the spatial modelling in GIS. Note that 'Grassland', 'Bushland' and 'Other' categories remain unchanged in the scenarios as presented.

Qualitative rules	Quantitative rules	Land cover group
Agriculture can expand where the climate is suitable and where there is sufficient dry season rainfall.	800 mm ≥ Annual rainfall ≤ 1800 mm *AND* 155 mm ≥ Dry season rainfall ≤ 740 mm	Agriculture
Agriculture can expand where the soils are good.	Soiltype[a] = 'CM', 'LV', 'FL' or 'AC'	Agriculture
Agriculture will tend to expand where the land is already near to a road and near to existing areas of agriculture.	Distance to road ≤ 20 km Distance to existing agriculture ≤ 20 km	Agriculture
Mainly in miombo and coastal habitats but not into plantations or grazing land or wetlands, except in the Kilombero Valley.	Land cover type ≠ urban Land cover type ≠ plantation forest Land cover type ≠ swamp *EXCEPT WHERE* Location = Kilombero	Agriculture
Certain districts will be targeted for expansion: along the coast; the Kilombero Valley; the area near to the town of Iringa.	District = Bagamoyo District = Kilombero District = Mvomero, etc.	Agriculture
There is no deforestation/cultivation of existing protected areas.	Management Type ≠ Protected Area (for Matazamio Mazuri) Management Type ≠ National Park/Game Reserve/Nature Reserve (for Kama Kawaida)	Agriculture
Woodland tends to occur in lower rainfall zones than agriculture and is less restricted by water in the dry season.	800 mm ≥ Annual rainfall ≤ 1400 mm	Woodland
Woodland will not expand into the existing forest because the climate is too wet.	Land cover type ≠ urban Land cover type ≠ plantation forest Land cover type ≠ upper-montane/montane or sub-montane forest	Woodland
Forest only occurs at higher elevations.	Elevation ≥ 500 m	Forest
Forest can only expand inside the existing mountain blocks.	Location = mountain block	Forest
Forest will not expand where there is existing agriculture or urban areas.	Land cover type ≠ urban Land cover type ≠ bare soils, rocks Land cover type ≠ agriculture	Forest

[a] Dominant soil type where CM = Ferralic Cambisols, LV = Humi-Rhodic Luvisols, FL = Humi-Gleyic Fluvisols, AC = Humic–Umbric Acrisols.

all of the conditional rules for that land cover type. Each land cover group had different rules so the size and extent of this spatial mask vary.

These spatial masks reduce the number of cells of the land cover map which are available for manipulation under the scenarios of change, but they still include a large number of individual 100 m grid cells. To determine which cells were the most suitable for change a weighting system was applied to the mask and this was derived through the consideration of four key attributes: accessibility to the main market of Dar es Salaam; proximity to a navigable road; proximity to existing areas of agriculture (for agricultural changes only); and climate suitability (Fig. 3). We describe each of these in turn below.

2.4.1. Accessibility to Dar es Salaam

Accessibility was quantified using the cost distance functions available in ArcGIS (ESRI, 2009); such approaches are well-established in accessibility modelling (DeMen, 2002; Adriansen et al., 2003). This technique requires two grid inputs: a target grid containing the location(s) to which travel distance is calculated, and a cost grid (sometimes called a friction surface) where each cell contains a value representing time or physical difficulty of crossing that cell. In our case, we were only interested in the relative accessibility of each location, so the units were not important. The approach is flexible and allows any number of variables to be included within the cost grid as long as high values represent high costs and vice versa. Our cost grid included a measure of the physical accessibility of each cell derived from the STRM digital elevation dataset by multiplying slope by elevation and then grouping the resulting values into ten equal classes and assigning them a score of 1 (low) to 10 (high). Existing transport routes were added to the grid and given a value of 1 – this low score ensures that those roads that do exist always remain favoured routes. In contrast, barriers to movement (both institutional and environmental) were given a score of 10 in the cost grid. Institutional barriers defined those areas where access was not permitted due to land ownership or use (for example – private plantations) whilst environmental barriers reflect those areas where access is restricted due to the nature of physical terrain and included large water bodies, rivers and permanent swamps.

Once the cost grid had been created, the cost distance from each cell to the target of Dar es Salaam was calculated using the standard functions of ArcGIS, incorporating both the Euclidean distance and the relative cost. Those cells with a cost distance less than 200 km were selected and then the values were grouped into four classes using Jenk's Natural Breaks – a standard method of classifying data into groups by optimising the breaks between classes by minimising the sum of squares error term (de Smith et al., 2006). For the agricultural mask, those cells nearest to Dar es Salaam received a score of 4, those furthest away received a score of 1, whilst those beyond 200 km received a value of 0. For the woodland and forest masks, this logic needs reversing, so those cells which are least accessible to the centres of population are those which were given higher ratings, reflecting the fact that land is most likely to revert to woodland when further away from people.

2.4.2. Accessibility to a navigable road

Workshop participants stressed the importance of the accessibility of a location to a navigable road, where navigable was defined as remaining passable by a vehicle all year round. Relatively few of Tanzania's roads are tarmac or of high quality. We selected those routes identified as main highways or good quality gravel roads from the available digital database, and checked these with Tanzanian experts. Four distance bands were defined: <1 km, 1–5 km, 5–10 km, 10–20 km and for the agricultural mask these bands were then assigned scores of 4, 3, 2 and 1 respectively. For the woodland and forest masks the same distance bands were used but these scores were reversed.

2.4.3. Accessibility to existing agriculture

Similarly, for the agricultural mask, those areas which were within 20 km of the existing agricultural front were zoned into <1 km, 1–5 km, 5–10 km, 10–20 km bands which were also weighted from 4 to 1, whilst the woodland and forest masks reversed these scores.

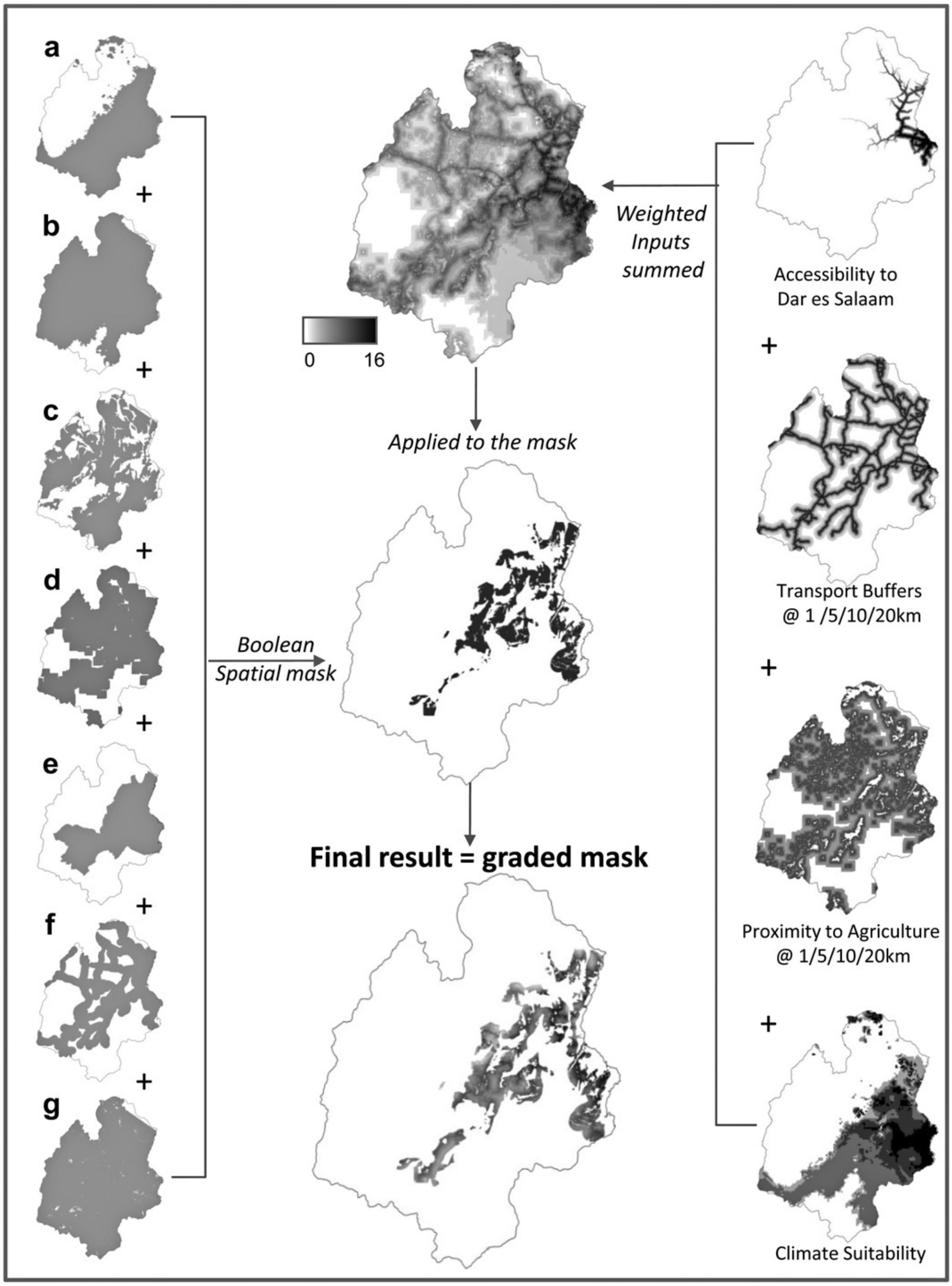

Fig. 3. Creating the weighted agricultural grid to constrain the land cover transitions demanded by the scenarios. The left hand side shows the construction of the initial Boolean mask with seven input grids, one for each rule described in Table 3 as follows: (a) = annual precipitation, (b) = dry season precipitation, (c) = suitable soils, (d) = areas within 20 km of existing agriculture, (e) = targeted administrative districts, (f) = within 20 km of roads, (g) = suitable land cover groups. The right hand side shows how the spatial mask is refined through a weighting process. Each of the four inputs was classified into 0–4 and then summed to produce a weighted grid with values from (0) unsuitable to (16) most suitable. The weighted grid is then combined with the spatial mask to produce the final graded mask for agriculture.

2.4.4. Climate suitability

Small-scale subsistence farming is widespread across the study area. In the absence of detailed cropping maps for our study region, we estimated which currently non-farmed areas were most suited for crop production by overlaying the current distribution of the main plantation crops (tea, rubber, rice, sisal and sugarcane – obtained from our 30 class land cover map) with annual and dry season precipitation data to derive a climate space for each crop. Currently non-farmed areas which lay within a given crop's climatic range were then given a value of one (with all other cells scored 0). Scores for each crop were then summed and split into 4 classes using Jenk's Natural Breaks to give a grid with suitability values ranging from 0 (least suitable) to 4 (suitable for the largest number of crop types).

A suitable climate space for the woodland class was defined using precipitation ranges listed for the Eastern Miombo ecoregion defined by World Wildlife Fund (Olson et al., 2001), while the montane tropical forest zone was defined using elevation and the mountain boundaries.

2.4.5. Constructing the graded suitability maps

Each of the weighted grids previously described had values in the range 0 (not suitable) to 4 (most suitable). These datasets were summed to give a final output grid with values between 0 (totally unsuitable) to 16 (most suitable) in the case of agriculture (Fig. 3). For the forest and woodland, three weighted grids describing accessibility to Dar es Salaam, accessibility to navigable roads and suitable climate were combined giving a range of between 0 (unsuitable) and 12 (most suitable). For each of the spatial masks previously described in Section 2.4, the suitability values were then applied thereby pinpointing which cells within the areas outlined by the spatial masks would be most likely to change from one land cover type to another (Fig. S2).

2.4.6. Implementing the changes to create the new land cover maps

In the MM example (Fig. 2) the key changes to be implemented are as follows:

- Mixed with crops GAINS 2.9% of the total area from Woodland.
- Agriculture GAINS 1.9% of the total area from Mixed with crops.
- Agriculture GAINS 0.1% of the total area from Forest.
- Forest GAINS 0.1% of the total area from Grassland (note this reflects expansion of plantation forestry not montane forest).
- Grassland GAINS 0.1% of the total area from Woodland.

In the KK example (Fig. S2) the key changes to be implemented are as follows:

- Mixed with crops GAINS 3.0% of the total area from Woodland.
- Agriculture GAINS 2% of the total area from Mixed with crops.
- Mixed with crops GAINS 1% of the total area from Forest.
- Agriculture GAINS 1% of the total area from Woodland.
- Agriculture GAINS 1% of the total from Forest.

By capturing all of the gains, the losses are automatically accounted for as the totals match between the start (in 2000) and the end (in 2025). In both scenarios the changes were programmed in turn from the largest total area change to the smallest. After each step an interim land cover product was created which then formed the input to the next change. In each case the area available to select from was defined by the weighted spatial mask created for each land cover group (Fig. 3) using the suitability grading to define which of the 100 m cells within the mask were chosen first.

These steps are described in more detail in the pseudocode in Fig. S3, and were programmed with ArcGIS© software (ESRI, 2009).

2.5. Estimating change in ecosystem service production and value – carbon storage in the Eastern Arc Mountains

The scenario modelling described in Section 2.4 yielded two land cover maps (MM 2025 and KK 2025) alongside the baseline dataset. The final step in linking our qualitative narratives to quantitative models involved using these land cover datasets as input to the carbon module of a GIS-enabled ecosystem services assessment tool called InVEST which uses a look up table for each land cover type to estimate carbon storage (Nelson et al., 2008, 2009; Daily et al., 2009).

Carbon storage values were derived for each of the 30 land cover classes present in the study region. Estimates for five storage pools (live aboveground, coarse woody debris, litter, belowground and soils) were extracted from the published literature (71 studies) and from unpublished data collected by Tanzanian researchers (6 studies; S. Willcock et al., unpublished data). To derive a single value for each land cover category each of the published sources was weighted, firstly by region and then by the sample size of the study. This ensured that carbon estimates for studies in Tanzania carried more weight than those outside the study region with more comprehensive studies with larger sample sizes carrying more weight than those with few values. Soil carbon values were obtained to a standard 1 m depth from the SOTER soils database (Batjes, 2004). In cases where we obtained less than six studies for a given carbon pool in a given land cover class we used the known aboveground live carbon pool and published ratio's between aboveground and other pools to estimate the carbon pool with few samples (IPCC, 2006). Bootstrap sampling was then used to produce the median carbon values and the 95% confidence intervals.

The literature review showed that our knowledge of the carbon storage capacity of many of the lowland bush-type habitats of Tanzania is still limited. In contrast, a great deal more attention has been given to the carbon storage potential of the woodlands and forests (Munishi and Shear, 2004; Lewis et al., 2009). We therefore, restricted our modelling to the upland landscapes of the four north-eastern mountain blocks of the EAMs: North Pare, South Pare, West Usambara and East Usambara (Fig. 1). Finally, we then used modest carbon values (~$15 per Mg) to calculate indicative changes in the value of carbon stored under the MM and KK scenarios.

3. Results

3.1. The MM and KK 2025 land cover maps

The MM and KK maps (Fig. 4) both show that changes from the present land cover map are dominated by changes in the eastern and central areas. Agricultural expansion within the coastal plain and along accessible routes is a common feature of both maps and is particularly marked in areas of pre-existing cultivation where accessibility to a market is already relatively good.

Under MM there is very little change to the distribution and cover of the tropical forests as all are assumed to be well protected and governed. Agricultural expansion is limited to areas outside the protected area network and is marked around the major coastal cities with the gradual expansion of existing cultivation into the woodlands and bushland, reflecting ongoing woodland degradation for food and fuel where no resource protection is in place (Mwampamba, 2007).

The KK scenario shows much more dramatic change, with the forest reserve network opened up to degradation and conversion. Some of the most important areas of tropical montane forest are situated close to densely populated areas where agriculture is already well developed and expanding. One such area lies inland from the port of Tanga, and includes four of the 13 mountain blocks, all of which are severely impacted under KK.

3.2. Impact of changing land cover on potential carbon storage

In 2000 the four focal mountain blocks had mean carbon densities of 140, 126, 119, 128 tonnes/ha^{-1} for North Pare, South Pare, West Usambara and East Usambara respectively. Total carbon storage was 8, 22.5, 37.1 and 16.6 million tonnes respectively (Fig. 5). Although West Usambara has the largest total area of forest of the four blocks, it also has largest area of agriculture (which stores little carbon) resulting in a lower mean density (Table 4).

Under MM, only two of the mountain blocks are affected by land cover change with the West Usambara and the East Usambara losing 0.8 and 2.5 million tonnes of carbon respectively, amounting to an overall 3.8% loss. Under KK all four mountain blocks are

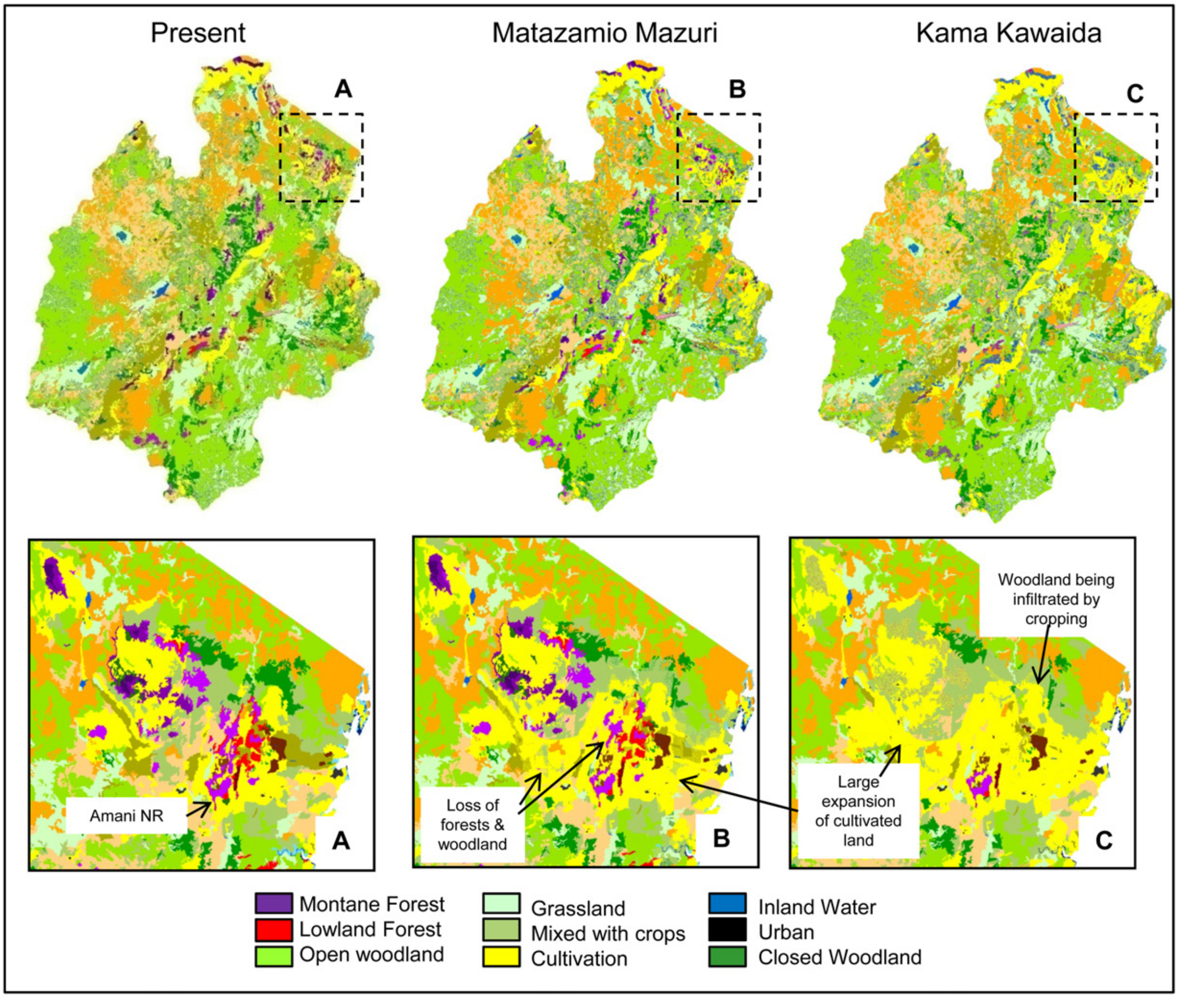

Fig. 4. Land cover maps for 2000, and 2025 under the Matazamio Mazuri and Kama Kawaida scenarios, with insets detailing changes in the north-east of the study area.

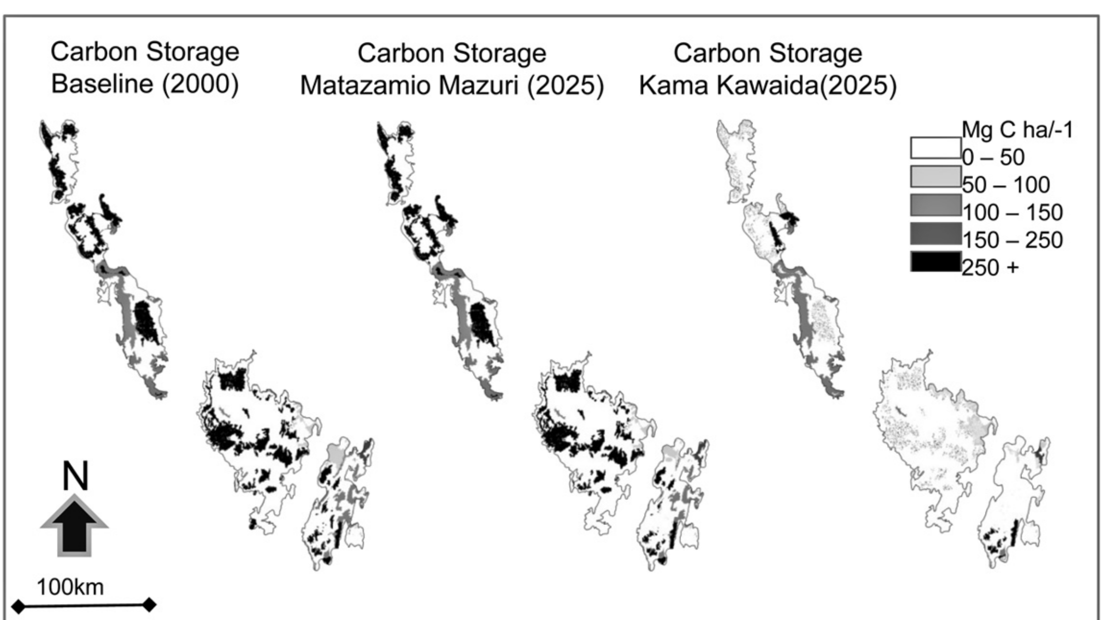

Fig. 5. The four focal mountain blocks of the north-eastern EAMs, showing changes in the spatial distribution of carbon storage by block and overall changes in carbon storage (tonnes).

Table 4
Estimated carbon storage in the north-eastern mountain blocks of the Eastern Arc Mountains modelled for the present landscape and for the two scenario landscapes showing total values with % change in brackets. Carbon values reflect a market value of $15 per tonne.

	Mountain block	Area (ha)	Current	Scenarios for 2025	
				MM	KK
Carbon storage (million/tonnes)	North Pare	57,395	8.0	8.0 (0%)	4.4 (−45.5%)
	South Pare	177,875	22.5	22.5 (0%)	14.8 (−34.0%)
	West Usambara	311,722	37.1	36.3 (−2.0%)	21.7 (−41.6%)
	East Usambara	129,835	16.6	14.1 (−15.0%)	9.2 (−44.5%)
	Total		**84.2**	**80.9 (−3.8%)**	**50.1 (−40.5%)**
Value	($millions)		1263	1214	751
Potential loss	($millions)			49	512

heavily impacted by forest and woodland losses. Total carbon storage drops to 4.4, 14.8, 21.7 and 9.2 million tonnes in the North Pare, South Pare, West Usambara and East Usambara respectively, with concomitant declines in the mean densities to 76, 83, 70 and 71 tonnes/ha^{-1}. Overall this amounts to a 40.5% decline in total carbon storage (Table 4).

4. Discussion

In this paper we have described a method to develop qualitatively derived scenarios into quantitative maps for use in ecosystem service modelling and valuation and have illustrated its use to value carbon stocks over a mountain region. Two socio-economic scenarios were formulated and parameterised in order to create alternative land cover futures for eastern Tanzania. The impact of changes in the distribution of key land cover classes was illustrated using a carbon model which showed that under the business-as-usual KK scenario the northern mountain blocks of the EAMs could lose as much as 41% of their present carbon storage if charcoal extraction and agricultural expansion continue unabated, especially if existing forest reserves in the mountains are poorly protected from such disturbance and degradation. MM (a more sustainable future) showed losses by 2025 of 3.8%. Analysis within the EAM showed that losses were variable and influenced by location, but the protected area network appears to play an important role in maintaining carbon stocks. Although the KK scenario shows large potential losses in the northern EAM, the precedent for such a decline is seen today in the severe degradation experienced by the lowland coastal forests close to Dar es Salaam, which have been heavily exploited to meet timber and charcoal demand in the capital, including protected forests (Ahrends et al., 2010).

Results generated by the carbon model used to illustrate the use of the output scenario maps are preliminary and will require further refinement. Estimating carbon storage where field surveys are relatively rare will inevitably be inaccurate so we adopted a regional approach to the source of our input values, favouring local studies (Tanzanian and East African) over those from elsewhere. A number of global carbon maps indicate lower estimates for aboveground carbon storage in the landscape of Tanzania (Hurtt et al., 2006; Baccini et al., 2008) than estimated in this study. This difference is likely due to the more limited forest inventory datasets used in the previous studies, and the lack of more regionally appropriate data from the EAM. The total carbon storage values used here were found to be comparable to those of Ruesch and Gibbs (2008), which used a larger forest dataset. Stratified random samples of each land cover class for each of the five major carbon pools are needed to make robust estimates of total carbon storage across the eastern Tanzanian landscape. While much effort is required to reach this target, the outline patterns are clear, with high carbon storage in forests, lower in woodlands, and lowest still in agricultural lands, strongly suggesting that our broad conclusions are robust.

The two scenarios presented show how it is possible to move from the narrative to the quantitative by developing rules built during the participatory scenario-building phase. In our case, no new rules were created after the workshops, and none were discarded. However, the modellers were part of the workshops so could provide immediate feedback on whether (with the spatial datasets available) the rule could realistically be tackled, thereby reducing redundancy, helping to focus the discussions and avoiding arbitrary decisions without input from local experts. Our method does however, raise a number of other issues – specifically with respect to the level of detail captured and parameterised for analysis. When scenarios are generated through participatory approaches a balance needs to be struck between relevant detail and eventual modelling tractability. If scenarios are to be useful to decision-makers and civil society then they should be able to be run easily with different inputs rather than complex processes which require extensive new data inputs and detailed qualification before each new run. By using a two-step process which started with Boolean rules to act as the first filter, followed by a weighting process to identify relative preferences for change as the second, we retained sufficient flexibility to allow the later sampling stage to work. It is important to keep the method clear and simple if at all possible to ensure that the foundations for the valuation stage can be understood.

Further refinement of the rules is possible and it is envisaged that this will take the form of a further round of workshops with local Tanzanian experts where the first draft land cover maps presented in this paper will be examined in detail and the rules re-examined in light of these outputs. They are presented here as 'proof of concept' of the method and the output should not be viewed as definitive. From a modelling standpoint, data issues need careful examination with respect to both scale and quality. This is particularly pertinent in locations where a national geospatial framework is lacking – as in Tanzania. All of the modelling presented here was undertaken with a 100 m grid – a scale determined by the structure of the key datasets (which in this case were land cover, elevation, the road network and settlements). Some of the relevant Tanzanian data require further improvement, most notably the soils dataset. Ideally, a land capability assessment is needed to identify those areas which have good soils for agriculture but such information is not available for large areas, nor is it necessarily in a form suitable for spatial modelling. Likewise, the land cover dataset which underpins our mapping is also known to be imperfect due to the well-documented problems of properly characterising the heterogeneous, wooded ecosystems and bushlands of sub-Saharan Africa (Sedano et al., 2005). As new datasets become available, it is hoped to improve these inputs to the modelling process. In the meantime, the problems in land cover definition need to be made clear to end-users.

One further issue not dealt with explicitly in this approach has been the distinction between differences in the areal extent of a land cover type and its condition. This is most pertinent to the issue of woodland and forest cover and the impact such changes can have on the production and delivery of ecosystem services. This is captured in a partial manner through the changes which are modelled between woodland and forest land cover types and the 'mixed with cropping' land cover type. There is an implicit degradation gradient contained within this change which is reflected in the carbon values afforded to these mixed categories, but it is possible that the values assigned to these degraded ecosystems are poor estimates as detailed field studies of degraded forest systems in Tanzania are not yet complete.

Consideration must be given to the communication of these results to end-users. There is little doubt that maps are powerful visual tools allowing complex information to be conveyed to a wide audience (Burnett and Kalliola, 2000). Ecosystem services are essentially spatial in nature; therefore, it makes sense to present the results of analysis of such services with maps, allowing details to be visualised across a large region. Maps allow us to move on from generic statements such as 'agriculture will expand' to specific statements of where this might happen. In addition, they can capture this information in a visual way that often commands the attention of decision-makers in a manner that statistical reports alone often do not. However, there is a danger that a mapped scenario can be seized upon as a definitive result. Individuals can be distracted by details, and experience has shown that almost all will focus in on relatively small areas they may know well to check the maps against their own experience and expectations for the future. In our example, the maps cover an area which is almost as large as Germany and it is at that scale that the scenario retains its spatial integrity – not at the level of an individual village. Making sure the end-users of such outputs are aware of this is important and requires careful communication. One way of mitigating this is to always present a number of scenarios together to reinforce the message of 'possible futures' based on a set of assumptions rather than 'the predicted future'.

Regional landscape modelling systems such as that constructed across the Amazon Basin in south America (Soares-Filho et al., 2004, 2006) or in the United States (US EPA, 2009) are not readily available for this part of Africa. So a bottom-up approach to scenario development and implementation was necessary in this case. Tapping into the expertise of local area experts can provide a very credible form of quality assurance which can carry weight with the local policy-makers. Even when (or if) automatically generated future landscape scenarios become available for Tanzania the regionally tailored approach detailed in this paper can still provide a valuable reality-check on the results.

5. Conclusions

Four clear messages emerge from our study: firstly that in order to generate quantitative insights into the consequences of alternative policy decisions, the participatory component of scenario-building must be clearly linked to quantitative modelling and these links at least partly envisaged beforehand; secondly complexity needs to be managed, otherwise time will be wasted in implementation; thirdly it is critical to think from the start about how policy and decisions are made in the particular region of study, otherwise a disconnect may arise between carefully constructed and modelled scenario exercises and the actual needs of the policy-makers for whom they are designed; fourthly such tailored scenario-building exercises can provide critical calibration of larger scale scenarios, ensuring the results do mirror local expectations of change. In our study, we were able to reflect on the experience of other published examples to design a simple process, which was practical given time and resource constraints and directly responded to a policy need of the Tanzanian government.

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jenvman.2010.09.007.

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