Scenarios of land use and land cover change and their multiple impacts on natural capital in Tanzania

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Scenarios of land use and land cover change and their multiple impacts on natural capital in Tanzania

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SUMMARY

REDD+ (reducing emissions from deforestation, and forest degradation, plus the conservation of forest carbon stocks, sustainable management of forests, and enhancement of forest carbon stocks, in developing countries) requires information on land use and land cover changes (LULCC) and carbon emissions trends from the past to the present and into the future. Here we use the results of participatory scenario development in Tanzania, to assess the potential interacting impacts on carbon stock, biodiversity and water yield of alternative scenarios where REDD+ is effectively implemented or not by 2025, the green economy (GE) and the business as usual (BAU) respectively. Under the BAU scenario, land use and land cover changes causes 296 MtC national stock loss by 2025, reduces the extent of suitable habitats for endemic and rare species, mainly in encroached protected mountain forests, and produce changes of water yields. In the GE scenario, national stock loss decreases to 133 MtC. In this scenario, consistent LULCC impacts occur within small forest patches with high carbon density, water catchment capacity and biodiversity richness. Opportunities for maximising carbon emissions reductions nationally are largely related to sustainable woodland management but also contain trade-offs with biodiversity conservation and changes in water availability.

INTRODUCTION

Many countries across the tropics face major challenges around meeting the needs of rapid developing and growing populations, maintaining viable ecosystem services while tackling the impacts of climate change through mitigation and adaptation strategies. The REDD+ mechanism has been proposed as a climate change mitigation framework with the potential for reducing greenhouse gas emissions while addressing rural poverty and conserving forest biodiversity and ecosystem services in the 2010 16th Conference of the Parties (COP 16) of the United Nations Framework Convention on Climate Change (UNFCCC). The international discussions on REDD+ evolved and diversified over time (Angelsen *et al.* 2012; Pistorius 2012; Lund *et al.* 2016), delivering hope, discouragement, support and criticism on its feasibility and capacity to provide win-win solutions to climate change mitigation - while also contributing to livelihoods, sustainable development, enhanced governance, and biodiversity conservation (Sunderlin *et al.* 2014; Pasgaard *et al.* 2016; Turnhout *et al.* 2016; Loft *et al.* 2017).

Tanzania started its REDD+ readiness process in 2008 (Burgess *et al.* 2010; URT 2010). The readiness process set the foundations and tested the carbon emissions monitoring, reporting and evaluation system (MNRT 2015). Tanzania also recently submitted its Intended Nationally Determined Contributions to UNFCCC (URT 2015); these give REDD+ related actions a central national role in both mitigation and adaptation contributions to climate change and development of a low emission growth pathway. More recently the country has submitted its Forest Reference Emission Level (FREL) to UNFCCC, currently undergoing technical assessment, which estimates annual deforestation rate at 580,000 ha year^{-1} over the 2002-2013 period (URT 2017). Several factors drive deforestation either directly (e.g. demand for farmland and biomass energy) or indirectly (e.g. high population growth rate, governance weakness and unsecure land tenure (Burgess et al. 2010, Kweka et al. 2015).

The Norwegian government funded a series of REDD+ pilot projects in Tanzania, which mainly focused on the local implementation of REDD+, in isolation from other policy mechanisms (Blomley *et al.* 2015). Although useful, these local insights are of limited use for scaling to the national context, or for creating long-term future sustainable development strategies (Abidoye *et al.* 2015). A key part of the REDD+ mechanism in Tanzania is to estimate trade-offs between carbon emission reduction and multiple co-benefits potentially achievable under REDD+, such as food and energy provisions, water availability and biodiversity conservation in relation to national development strategies (e.g. Tanzania Development Vision 2025, URT 2005). An initial assessment of potential REDD+ co-benefits in Tanzania (Miles *et al.* 2009; Runsten *et al.* 2013) has been followed by efforts to produce increasingly specific and nation-based datasets, analyses (Augustino *et al.* 2014), scenarios method (Capitani *et al.* 2016) and REDD+ Social and Environmental Safeguard Standards (VPO 2013a). In this study, we present a quantitative evaluation of the potential interacting impacts of two alternative socio-economic and land use and land cover changes scenarios (LULCC) on carbon stock and two non-carbon forest ecosystem services, biodiversity and water regulation. We analyse the spatial distribution of potential win-win or conflicting outcomes from the two scenarios. Then, we discuss the potential contribution of scenario analysis to the Forest Reference Emission level reporting, and for identifying potential sinergies or conversely preventing unintended impacts, within the framework of the Tanzania national climate change and development strategies and International pledges.

METHODS

Our study focused on the mainland of the United Republic of Tanzania, the largest country in East Africa with a population of 44.9 million people (NBS & OGCS 2013). Forests cover ca. 48.1 million hectares (Mha), corresponding to 55% of Tanzania mainland (National Forest Resources Monitoring and Assessment, NAFORMA, MNRT 2015). This figure is higher than estimates obtained from satellite data (38.3% in 2010, MNRT 2013). In Tanzania forests are managed either in protected areas- various designations comprising about half of the woody volume where forest management ranges from total protection (e.g. nature reserves) to regulated harvesting (e.g. forest reserves), or in 'village' and 'general land' (15.4 Mha, MNRT 2015). An estimated 4 Mha falls under community forest management regimes under Participatory Forest Management (PFM, MNRT 2008).

Scenarios development

We developed land use and land cover changes scenarios for Tanzania to 2025 following four-steps within a mixed participatory and modelling scenario framework (Supplementary 1.1) that engaged 240 stakeholders from civil society and authorities at local, regional and national level (WWF 2015, Capitani *et al.* 2016). First we broadly defined two alternative scenarios: the business as usual (BAU)- policies framework, demand for commodities, and implementation of REDD+ follow the current development trajectory, and the green economy (GE)- a shift toward sustainable practices is envisaged for agriculture, forestry and energy sectors supported by governance enforcement, effective REDD+ implementation, and enhanced productivity. Then, regional stakeholders developed locally tailored, qualitative and semi-quantitative scenarios trajectories, associated with specific spatial patterns and likelihood of LULCC. Next, LULCC scenarios were modelled by allocating demand for cultivated land and wood biomass according to LULCC likelihood spatial layers (Table S1), as expected by stakeholders and validated with secondary data. By using the national land use and land cover map for 2010 (MNRT 2013, Fig. S1a) as baseline and the World Database on Protected Areas (IUCN & UNEP-WCMC 01/2015), changes were modelled from specific land use and land cover classes to arable land (cultivation expansion), to mixed cultivated-wooded land (shifting cultivation), and to classes having lower tree cover and biomass without cultivation replacement (degradation, e.g. from closed woodland to bushland). Preliminary results were validated in a national level workshop in 2015 and refined thereafter to create the results presented here. The spatial resolution of scenario outputs was ca. 100 m. To maintain the local representativeness of change pressures in the national scale impacts assessment on carbon and non-carbon benefits, we applied a double resampling process that has reduced the accuracy of our analysis (see Discussion and Supplementary 1.2).

Carbon stock

Biomass carbon stock was estimated for the Tanzania mainland using a national dataset for above ground biomass (AGB, Ortmann 2014) based on NAFORMA forest inventory data, and from land-cover-specific ratios for below ground biomass (MNRT 2015), litter and deadwood biomass (Willcock *et al.* 2012). The wood dry matter biomass was converted to carbon by applying a 0.47 conversion factor, following the national protocol (URT 2017). Top soil organic carbon content for the 0-30cm layer was estimated by multiplying carbon concentration data from a national map

(Kempen *et al.* 2014) by the corresponding volume and bulk density obtained from the Soil and Terrain Database (SOTER) of Southern Africa (Dijkshoorn 2003). Both scenarios and the associated LULCC change imply C stock losses by 2025, though lower in the GE than in the BAU scenario (Capitani *et al.* 2016), reflecting the need of ensuring food and energy security, while allowing infrastructure development. For LULCC driven carbon stock changes estimate, the baseline (Fig. S2a) was created from biomass and top soil carbon datasets resampled from the original ca. 250-m resolution to ca. 100-m resolution by using the nearest neighbour method. We assumed that cultivation expansion depletes the five carbon pools, while shifting cultivation and degradation deplete the above ground and dead wood biomass only. For newly created cultivated land or shifting cultivation, carbon stocks in the scenarios were estimated as the average stock of the respective classes for the baseline. Carbon stock for degraded areas in the scenarios was estimated by decreasing the baseline biomass proportionally to the average biomass loss for the specific LULCC types expected in each pixel. Carbon stock changes were calculated as the pixel base difference between the baseline and the scenarios. The final results were then aggregated at 1-km resolution.

Biodiversity

We assessed the potential impacts of LULCC on biodiversity under the two scenarios focusing on terrestrial vertebrate species as derived from the IUCN Red List database (mammals, birds, amphibians and reptiles, IUCN, 2016 and BirdLife International & NatureServe 2015). Species sensitive to the modelled LULCC (hence LULCC-sensitive species) were selected following the IUCN classification of threats from cultivation expansion (threat class 2.1, 2.2.1), livestock rearing (class 2.3), wood harvesting for energy and timber (class 5.3), fire (class 7.1), and urbanization (class 1) (see Salafsky *et al.* 2008). For every species, extent of occurrences (EOO) layers in Tanzania were clipped to the occupied habitats by matching the associated IUCN habitat classes with global cover land use types (Foden *et al.* 2013) and then with our reference land use and land cover classes to generate Extent of Suitable Habitat (ESH) polygons. We collected spatial distribution data and generated ESHs for 164 amphibians, 311 mammals, 58 reptiles, 1002 birds species on the Tanzanian mainland. Out of these 1535 terrestrial vertebrates, 177 are either classified by IUCN (2016) as endemic (127) or included in the IUCN categories 'Critically Endangered, Endangered and Vulnerable' (hence threatened species, 140) or both (90). We calculated ESH reduction in the two scenarios for LULCC-sensitive species, focusing on endemic species and threatened species with at least 1% of their range included on the Tanzania mainland. We calculated a spatially explicit biodiversity index prioritising species richness and rarity (BRRI, modified from van Soesbergen *et al.* 2016, Fig. S2b,) across Tanzania at 1-km resolution, by summing over all occurring species in each grid-cell (richness) the ESH weighted by the species distribution range size in Tanzania and over the globe (rarity, see Supplementary 1.3 for equations).

Water yield

To assess the impacts of LULCC under the two scenarios on water yields we used the WaterWorld V2 (Mulligan 2013) model at a resolution of 1 km. WaterWorld is a fully distributed, process-based hydrological model that utilises remotely sensed and globally available datasets. Baseline climate data is based on a long term climatology from WorldClim (Hijmans *et al.* 2005). Land use and land cover in the model is represented by fractional values for three functional vegetation types (tree, herb and bare). We calculated these fractional values for each land use class in the baseline and scenarios using the nearest mean fractional value for a group of cells of that class for MODIS VCF data for the year 2010 (DiMicelli *et al.* 2011) thus retaining variability within land use classes as well as within country. Calculations were made at the ca. 100-m scenario resolution by resampling the MODIS VCF data. Final baseline and scenario fractional vegetation maps were then aggregated to 1-km resolution and used to run the model. Changes in water yields under each scenario were analysed as changes in pixel based water balance in mm year^{-1} between the baseline (Fig. S2c) and the scenarios.

Multi-dimensions scenarios assessment

We assessed spatial patterns of synergies and trade-offs between carbon stock, biodiversity and water yield changes in the two scenarios. We focused on LULCC subjected areas, though we acknowledge that impacts could also be reflected outside, particularly for water. Changes in the three dimensions compared to the baseline were standardised, based on the scenarios and baseline statistical distribution of each dimension, and merged into a composite Red-Green-Blue (RGB) plot. We defined as increasing impacts between the scenarios and the baseline the decline of C stock, of BRRI index, and either positive or negative changes in water yield diverging from 0. Here, we report and discuss trade-offs across scenarios by comparing high to low impacts on the three dimensions.

RESULTS

In the BAU scenario, cultivated land is expected to expand by 5.4 Mha (0.36 Mha year^{-1}) by 2025 (Fig. S1b). In addition, shifting cultivation expands over 3.5 Mha (0.23 Mha year^{-1}) and degradation over 3.4 Mha (0.22 Mha year^{-1}) by 2025. In the BAU scenario, 11% of LULCC occur within protected areas, mainly in state managed forest reserves. In the GE scenario (Fig. S1c), cultivation expansion is reduced to 4.5 Mha (0.3 Mha year^{-1}) and degradation occurs over 3.6 Mha (0.23 Mha year^{-1}).

Carbon

In the BAU scenario, the envisaged land cover changes are estimated to result in ca. 296 million tonnes of carbon (MtC) national stock loss by 2025 compared to 2010. The countrywide estimated carbon stock loss in the GE scenario is ca. 133 MtC by 2025 (Fig. 1). In the GE scenario, 37 MtC avoided emissions within protected areas accounts for 23% of the emissions difference compared to the BAU scenarios. Countrywide the C stock changes mostly occur within open woodland in both scenarios, ranging between 58% (GE) and 65% (BAU) of total change (Table 1). Under the GE scenario, following forest protection and sustainable management enforcement LULCC are partially displaced to habitats with lower management safeguards, such as bushland, grassland and mangrove forests.

Biodiversity

In the BAU scenario 326 LULCC-sensitive species are impacted by habitat conversion; this includes 100 Tanzania endemic and 120 threatened species. In the BAU scenario the extent of suitable habitat (ESH) reduction averages 20% for the endemic species and 6.5 % for the 37 non-endemic threatened species. Under BAU six species (*Arthroleptis kutogundua*, *Afrixalus morerei*, *Churamiti maridadi*, *Galagoides rondoensis*, *Nectophrynoides laticeps* and *Nectophrynoides paulae*) lose

50% or more of their ESH. In the GE scenario, 317 LULCC-sensitive species are impacted by LULCC. The mean ESH reduction decreases to 4% for the 91 impacted endemic species and to less than 1% for the 36 non-endemic threatened species. The biodiversity richness and rarity index (BRRI) is highly variable across Tanzania, with the highest values mainly concentrated within the Eastern Arc Mountains (EAM) biodiversity hotspot (Meng *et al.* 2016, Fig. S2b). In both scenarios (Fig. 2), the highest potential impact in high BRRI areas occurs in mountain forest patches. Compared to the Ge scenario, in the BAU scenario BRRI losses were locally higher, due to larger habitat losses of LULCC-sensitive species, but the BRRI gains were slightly wider, due to generalist species expansion in habitats with reduced canopy compared to the baseline. In the GE scenario, BRRI losses extended in species-rich regions not exposed to LULCC in the BAU scenario.

Water yield

Changes in water yields, expressed as changes in water balance, are greater under the BAU scenario than the GE scenario, with a mean increase in water balance of 3.9 mm year^{-1} (+2%) versus 1.9 mm year^{-1} (+1%), across BAU and GE scenario respectively (Fig. 3). Under the BAU scenario, nearly 10% of the country sees a change in water balance of more than 50%, while under the GE scenario this is 6.2%. In both scenarios mountain and lowland forest and closed woodland face the most intensive changes in water balance (per hectare), but woodland and wetlands contribute the largest observed absolute change at national scale because they cover a much bigger area than forests. Increases in water yield are generally the result of land degradation, reducing the amount of water use by vegetation and thus increasing available water for runoff, more closely following the rainfall pattern. In addition to water use by vegetation, trees can also play an important role in 'capturing' occult precipitation within cloud forests (Bruijnzeel *et al.* 2011) and favouring precipitation infiltration within miombo (Kashaigili & Majaliwa 2013). In the baseline this contributes up to 17% of the water balance in montane forested areas of the Eastern Arc, the northern volcanoes, and in the west near lake Tanganyika. Forest degradation in those areas therefore is more likely to result in a reduction in available water.

Multi-dimensions scenarios assessment

The simultaneous assessments of impacts of LULCC on carbon, biodiversity and water yield gives a complex pattern for both scenarios. Few land use patches show matching degrees of impact (e.g. either low or high impact in every variable); while in most areas LULCC generate different combinations of impact intensity (Fig. 4). In the BAU scenario, simultaneous high impacts in every dimension are mainly focused in protected forests and woodlands across EAM and south-western Tanzania (Fig. 4). In the GE scenario, 40% of LULCC are avoided, and simultaneous high impacts on carbon, biodiversity and water yield decrease. Increased impact on carbon, biodiversity and water yield is more frequent outside managed areas. In the GE scenario, about 19% of LULCC occur in different areas than in the BAU scenario (potential displacement). In about one-third of displaced LULCC areas, low impact on carbon is associated with high impact on either biodiversity or water yield.

DISCUSSION

Studies that assess potential future trade-offs and interactions between carbon and non-carbon benefits of natural habitat conservation are rare for East Africa (e.g. van

Soesbergen *et al.* 2016). Synergies and trade-offs between ecosystem services, as their provision and demand change (Locatelli *et al.* 2013), with simultaneous assessment of carbon and non-carbon benefits at large scale being highly challenging (Busch & Grantham 2013).

In the highly diverse landscape of Tanzania, under land change scenarios spatial patterns of impacts on carbon storage, biodiversity and water yield are not homogeneous. Consistent patterns are identifiable to some extent in relation to the different habitats and forest management regimes. In montane and lowland forests LULCC driven impacts are usually consistent and result in high carbon stock loss, biodiversity loss and water yield change. This increased water availability could benefit farmers locally, but could cause severe impacts downstream (e.g. Enfors & Gordon 2007; Kashaigili & Majaliwa 2013). In species-rich dry woodlands of north-eastern Tanzania LULCC impact is higher on biodiversity than on carbon stock. In addition, cultivated land expansion result in relatively low rates of carbon stock loss per unit area but are locally associated with cumulated water deficit, and increased irrigation demand. Site-specific trade-offs between carbon and non-carbon benefits impacts require joined up action by decision-makers, for example management interventions that link water provision with carbon storage.

Lessons for REDD+ implementation

The Tanzania National REDD+ Strategy (VPO 2013b) identifies three broad categories of REDD+ implementation actions: improved management and restoration of protection and production forest reserves, community-based forest management (including non-reserved areas), and plantation forestry. Our findings suggest that strictly protected forests conserve carbon, preserve biodiversity and maintain the water catchment, albeit over relatively small areas. Sustainable management of productive forests can support carbon emission reduction in the GE scenario, but with trade-offs for biodiversity and water yield. Maximising the potential benefits depends on the simultaneous enforcement of management and adequate resolution of conflicts, while ensuring current and future human communities' needs are met (Persha & Meshack 2015). Critical to REDD+ implementation is the risk of avoiding deforestation leakage (Pfeifer *et al.* 2012). In the GE scenario, LULCC impacts on biodiversity shift from rare forest species to species-rich communities in semi-open habitats that have lower carbon value and hence of slightly lower priority in Tanzania REDD+ framework. This suggests that ambitious REDD+ targets are needed for carbon emission and habitat conversion reduction to meet biodiversity conservation objectives in Tanzania.

Protected areas and community-based forest management areas alone are not sufficient to achieve emission reductions required to fulfil the Tanzanian national commitment (URT 2015), meanwhile ensuring food, water and energy security to the increasing population. At the national scale in both scenarios most carbon stock changes, as well as water yield and biodiversity disturbance, are anticipated in general land, particularly focused along the commercial development corridors (e.g. SAGCOT and Tanga). Addressing land and natural resource degradation outside managed areas requires better integration of a landscape-centred REDD+ (Turnhout *et al.* 2016), development (e.g. poverty reduction, food security and education) and conservation policies based on broader consensus and engagement by a wide range of actors that have political will and support from Government ministries, NGOs and community based organisations.

The Forest Reference Emission Level (FREL) assessment for Tanzania estimated ca. 58 $MtCO_2$ $year^{-1}$ emitted due to deforestation (URT 2017), comparable to ca. 61 MtCO2 $year^{-1}$ estimated in the BAU scenario using the same deforestation definition, though a different methodology. Our demand driven LULCC scenarios provide a useful estimate on the magnitude of deforestation fraction not detectable from satellite images (Hojas-Gascon *et al.* 2015). The multi-dimensional quantitative assessment can contribute to ongoing national and international debates surrounding expectations for carbon and co-benefits values; these can be used to chart the triple wins or compounded losses of potential futures. The scenarios, and importantly the wider information behind these, can be used to support current negotiations of desirable or undesirable impacts across diverse beneficiaries of forest services, in relation to REDD+, the Intergovernmental Platform on Biodiversity and Ecosystem Services and the Sustainable Development Goals.

Caveats and limitations

As with all results from scenario analysis, our findings have inherent uncertainty. The presented results are not predictions but depict potential impacts within the range of our scenario trajectories. To maximise relevance and legitimacy, to represent multiple scale perspectives, interaction of key components of water, carbon and biodiversity, and to overcome consistent challenges of time series data quality and scarcity for Tanzania, we put great efforts in model and datasets customization. However, the uncertainties generated by this approach should be considered when drawing conclusions from the presented results.

Dataset resampling has affected the accuracy of impacts spatial patterns and of the multi-dimension assessment at pixel level. The choice of indices also influenced the presented findings. For example, the adopted biodiversity index has the advantage of being sensitive to LULCC. However, it does not consider other essential aspects of biodiversity (Supplementary 1.3) or interactions with other sources of disturbance (e.g. climate change disturbance (Foden et al. 2013). Prioritization of biodiversity and ecosystem services conservation should account for internal feedbacks characterised by connectivity and complementarity (Kukkala and Moilanen 2017), which are not captured by pixel-based analysis.

The selected thematic and temporal scopes influence our findings. Considering additional dimensions (e.g. social) and different impacts thresholds (e.g. negotiated amongst stakeholders) could change the outcomes of multiple co-benefits assessment. The limited scenarios temporal horizon was set to comply with tangible objectives such as the Tanzania Development Vision 2025 (URT 2005) and the REDD+ roadmap, but this could limit the scope for green development assessment.

In respect to the relevance for supporting decision making, we successfully engaged with a broad range of stakeholders from across the country to co-produce scenarios, build local assessment capacity and consensus around the scenarios outputs. Such approaches need integrating into institutional frameworks to effectively influence policy formulation and implementation to mainstream biodiversity conservation and ecosystem services provision in future land use planning.

Supplementary material

For supplementary material accompanying this paper, visit www.cambridge.org/core/journals/environmental-conservation

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FIGURE LEGENDS

Figure 1. Changes in total carbon stock (carbon tonnes per hectare, C t ha^{-1}) in the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025.

Figure 2. Changes in biodiversity richness and rarity index (BRRI) for terrestrial vertebrates in the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025. Negative and positive changes relates to prevalent losses and gains of species suitable habitats, respectively.

Figure 3. Changes in water yields per year (mm $year^{-1}$) in the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025. In both scenarios yield increment (blue shades) compared to the baseline is more frequent than yield decrease (red shades).

Figure 4: Red-Green-Blue (RGB) plot of combined impacts on carbon stocks (black to green), biodiversity (BRRI, black to red) and water yield (black to blue) under the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025. Areas mapped in black indicate low impact values and light colours high impact values for all three dimensions. The three-dimensional legend is represented in two visions at the bottom left of the figure. The upper vision shows, for each cube face, the colour combinations of the three dimensions when one is at its maximum value and the other two are varying. The lower vision shows, for each cube face, the colour combination of the three dimensions when one is at its lowest value and the other two are varying.

Table 1. Share of carbon (C) stock changes (million tonnes, Mt, and percentage of the total land cover class C stock, %) by different land cover classes in the business as usual (BAU) and green economy (GE) scenarios. Classes are grouped according to the national definition of forests, other wooded land and other land, URT 2017. Carbon stock losses in the BAU scenario within protected areas (PAs) are reported separately.

	BAU	BAU: losses within PAs	GE
	C Mt - (%)	C Mt - (%)	C Mt - (%)
Forests			
Mountain & lowland forest	6 (5)	4 (3)	<1 (<1)
Closed woodland	42 (7)	5 (1)	5 (1)
Open woodland	192 (20)	4 (2)	79 (8)
Mangrove forest	<1 (3)	<1 (<1)	<1 (5)
Thicket	3 (21)	<1 (<1)	0 (0)
Other wooded land			
Bushland	33 (9)	2 (<1)	39 (10)
Grassland	5 (3)	<1 (<1)	8 (6)
Other land			
Wetlands	15 (19)	2 (2)	5 (6)

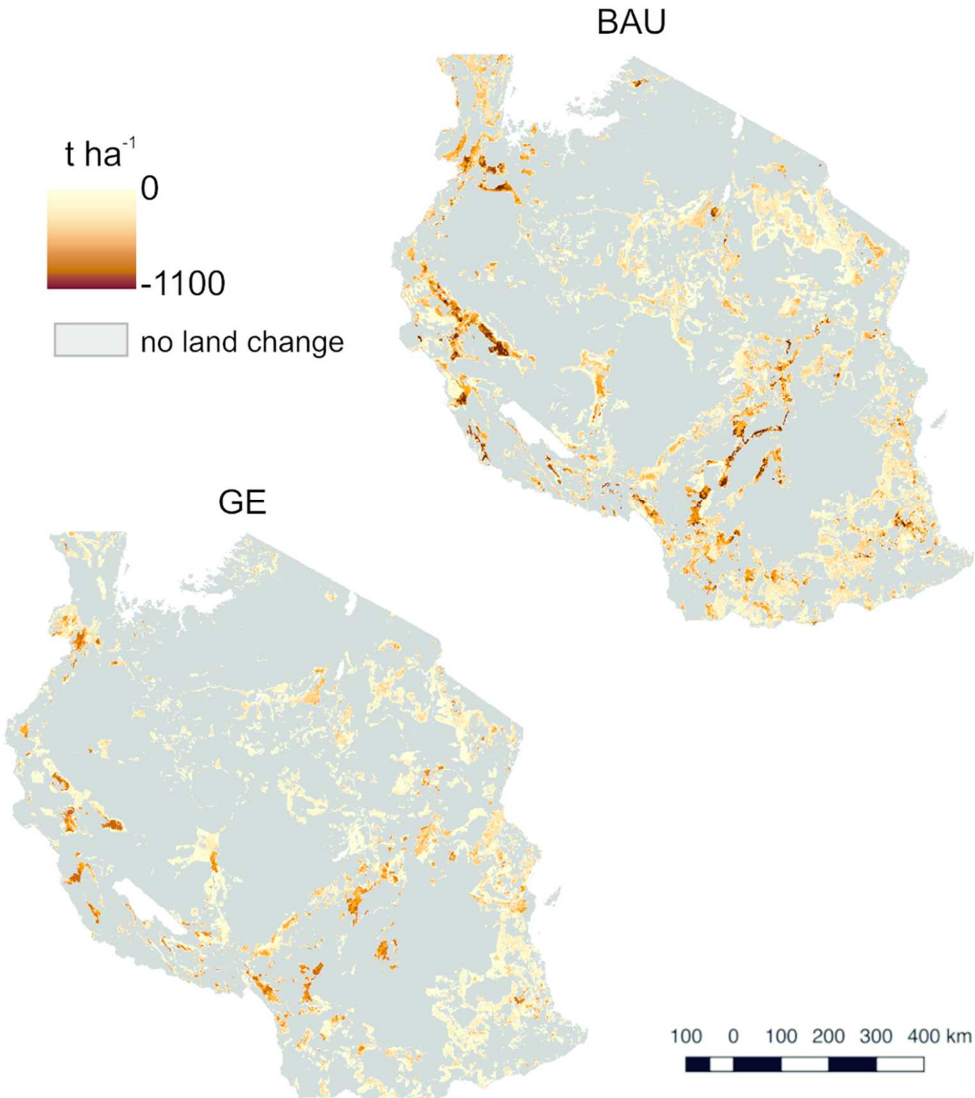

Figure 1. Changes in total carbon stock (carbon tonnes per hectare, C t ha-1) in the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025.

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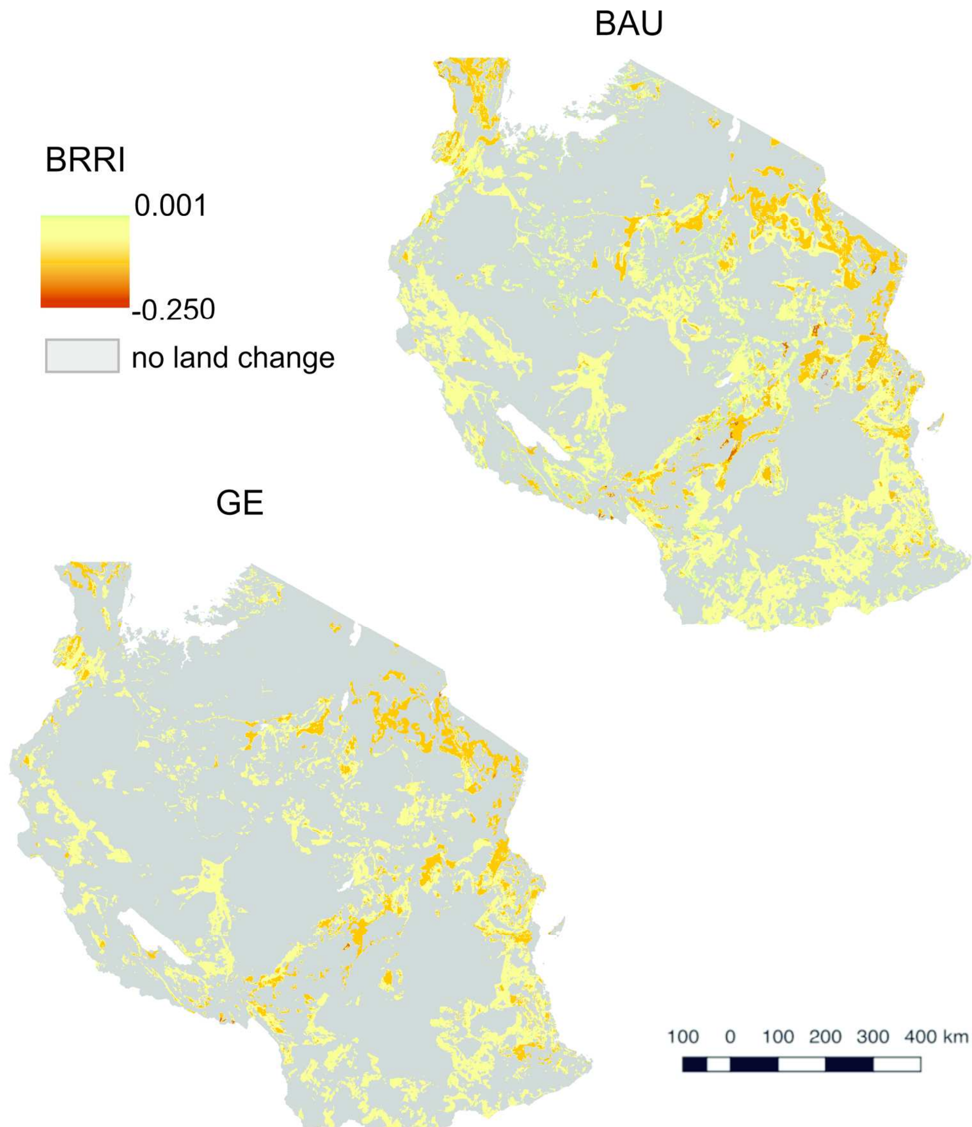

Figure 2. Changes in biodiversity richness and rarity index (BRRI) for terrestrial vertebrates in the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025. Negative and positive changes relates to prevalent losses and gains of species suitable habitats, respectively.

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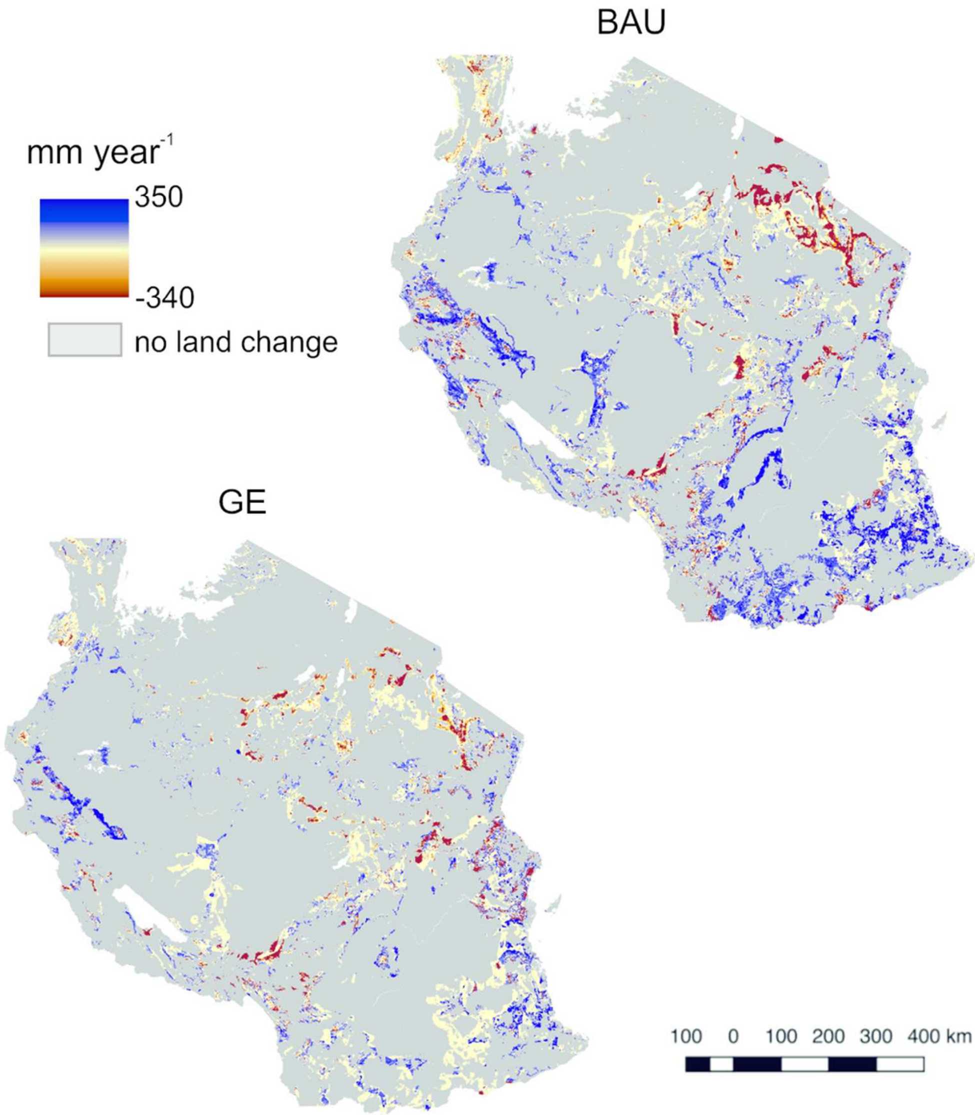

Figure 3. Changes in water yields per year (mm year-1) in the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025. In both scenarios yield increment (blue shades) compared to the baseline is more frequent than yield decrease (red shades).

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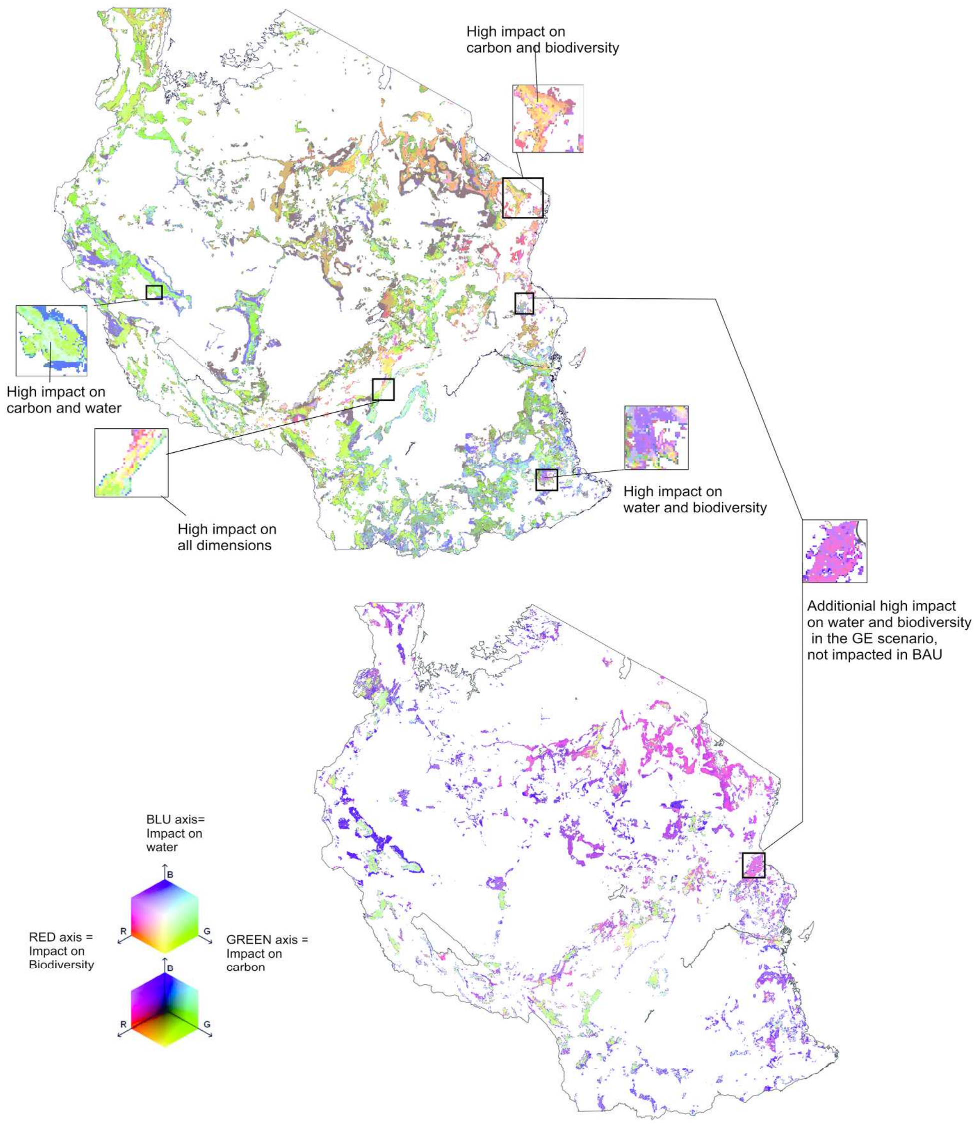

Figure 4: Red-Green-Blue (RGB) plot of combined impacts on carbon stocks (black to green), biodiversity (BRRI, black to red) and water yield (black to blue) under the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025. Areas mapped in black indicate low impact values and light colours high impact values for all three dimensions. The three-dimensional legend is represented in two visions at the bottom left of the figure. The upper vision shows, for each cube face, the colour combinations of the three dimensions when one is at its maximum value and the other two are varying. The lower vision shows, for each cube face, the colour combination of the three dimensions when one is at its lowest value and the other two are varying.

99x119mm (600 x 600 DPI)

Supplementary material – (.pdf 722 Kb)

This Supplementary provides details on the scenario development framework; the baseline maps for carbon and non-carbon benefits assessment, along with caveats and potential sources of error in datasets manipulation; and, the biodiversity richness and rarity index.

1.1 Scenarios development framework

Our scenario development framework aimed to tackle the challenges of translating qualitative narratives into quantitative scenarios incorporating indigenous and local knowledge. Following a mixed participatory and modelling framework (Table S1), our approach allows translation of stakeholders' developed qualitative and semi-quantitative scenarios trajectories and land use and land cover change patterns into quantitative and spatially explicit information.

Table S1. Steps of the participatory scenario development framework

Step 1 Scenarios definitions	Business as usual: policy framework, demand for commodities, and implementation of REDD+ follow the current development trajectory. Green economy: shift toward sustainable practices for agriculture, forestry and energy sectors supported by governance enforcement, effective REDD+ implementation, and enhanced productivity.
Step 2 Scenarios developm ent by stakeholde rs	a) Development of qualitative and semi-quantitative socio-economic and environmental trajectories of change and relative drivers by main livelihood sectors identified at regional level by multiple stakeholders. b) Identification of specific spatial patterns of land use and land cover changes (LULCC) related to expected trajectories and drivers of change (e.g. "*high likelihood of conversion from closed woodland to*

	grassland due to charcoal production near roads and in districts where governance is weak in region X”).
Step 3 Modeling	a) Quantification of demand for cultivated land and wood biomass according to secondary data[1] and expected trajectories. In this study, the business as usual scenario refers to the BAU2 quantitative scenario detailed in Capitani et al. (2016; Appendix 2). Business as usual: 30% expansion for both cultivated and mixed cultivated-wooded land; pro-capita annual wood volume demand = 0.87 m^3. Green economy: 10% increase in crop productivity no expansion of shifting cultivation; 50% reduction of wood biomass harvesting exceeding available sustainable cut. b) Spatial allocation of LULCC based on scalar composite indicators of likelihood of change calculated for different types of LULCC following the stakeholders’ assessment and calculated from global and national reference datasets (corrected through locally obtained information when necessary)[1] according to the formula: $$SI_{lulcc} = (sp_1 + sp_2 + sp_3) \times m \times pas$$ SI_{lulcc}, composite indicators of likelihood of each specific LULCC; reclassified and standardized spatial datasets affecting LULCC likelihood (sp_n); m = 0/1 masking factor derived from crop suitability and slope to mask out unsuitable areas for cultivation expansion; pas, protected areas mask used to limit LULCC likelihood according to the rules: likelihood of LULCC occurring within protected areas decreasing

	with the distance from protected areas border in the BAU scenario (pas decreasing from 1 to 0); LULCC not occurring within protected areas in the GE scenario (pas = 0). Demand for land and for biomass is allocated through specific LULCC from the pixels with the highest likelihood of change until demand is fulfilled.
Step 4 Iteration	Validation of preliminary results, feedback and synthesis workshop with regional and national stakeholders; model and outputs refinement.

[1] See Appendix 2 Capitani et al. 2016.

1.2 Scenarios and baseline maps

The scenario outputs (Fig. S1) were generated with a spatial resolution of ca. 100 m, in agreement with the population density dataset (WorldPop, Tatem 2017[i]), representing one of the major driving forces of land changes in our scenarios. Impacts from land use and land cover change scenarios in Tanzania on carbon, biodiversity and water yield were calculated using datasets derived from different inputs, at different resolution and with different methods (Fig. S2).

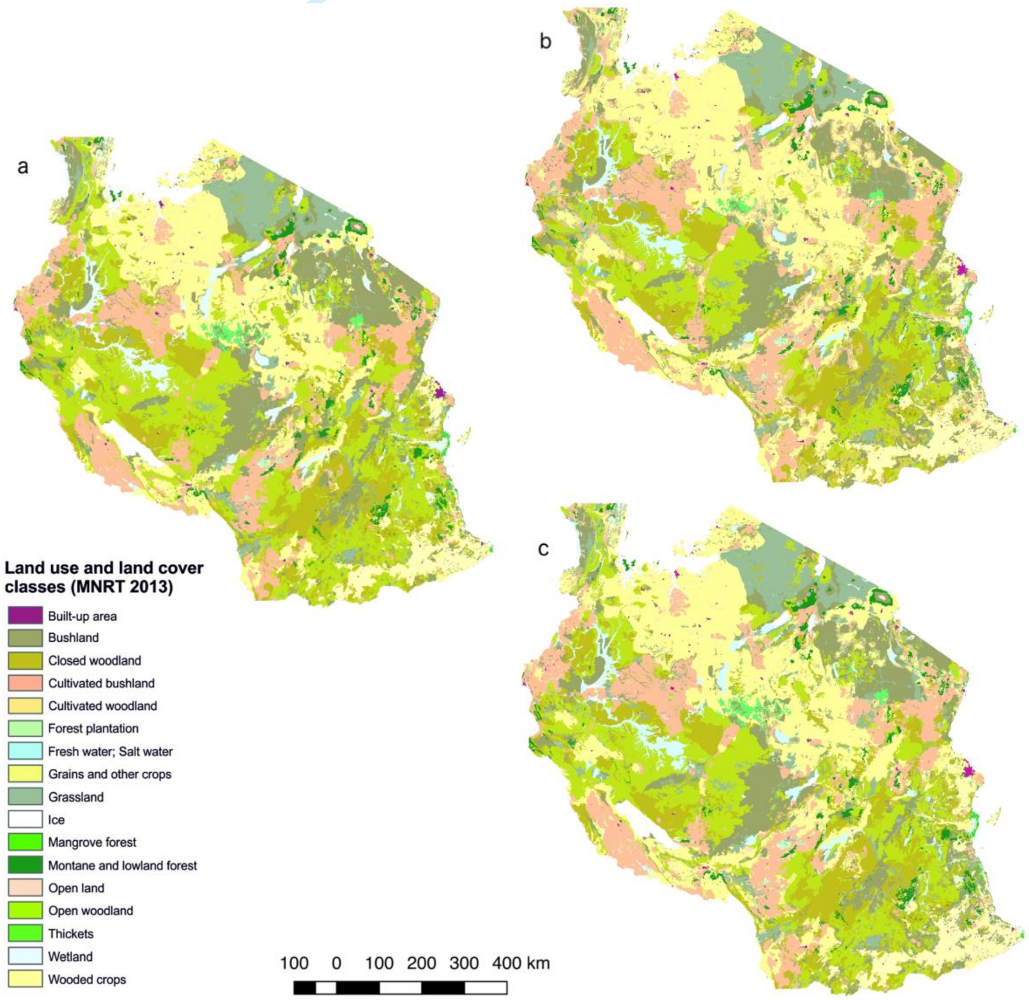

Figure S1. Land use and land cover reference map for 2010 (a, MNRT 2013) and for b) the business as usual and c) the green economy scenarios. Scenario output maps can be obtained upon request from the authors.

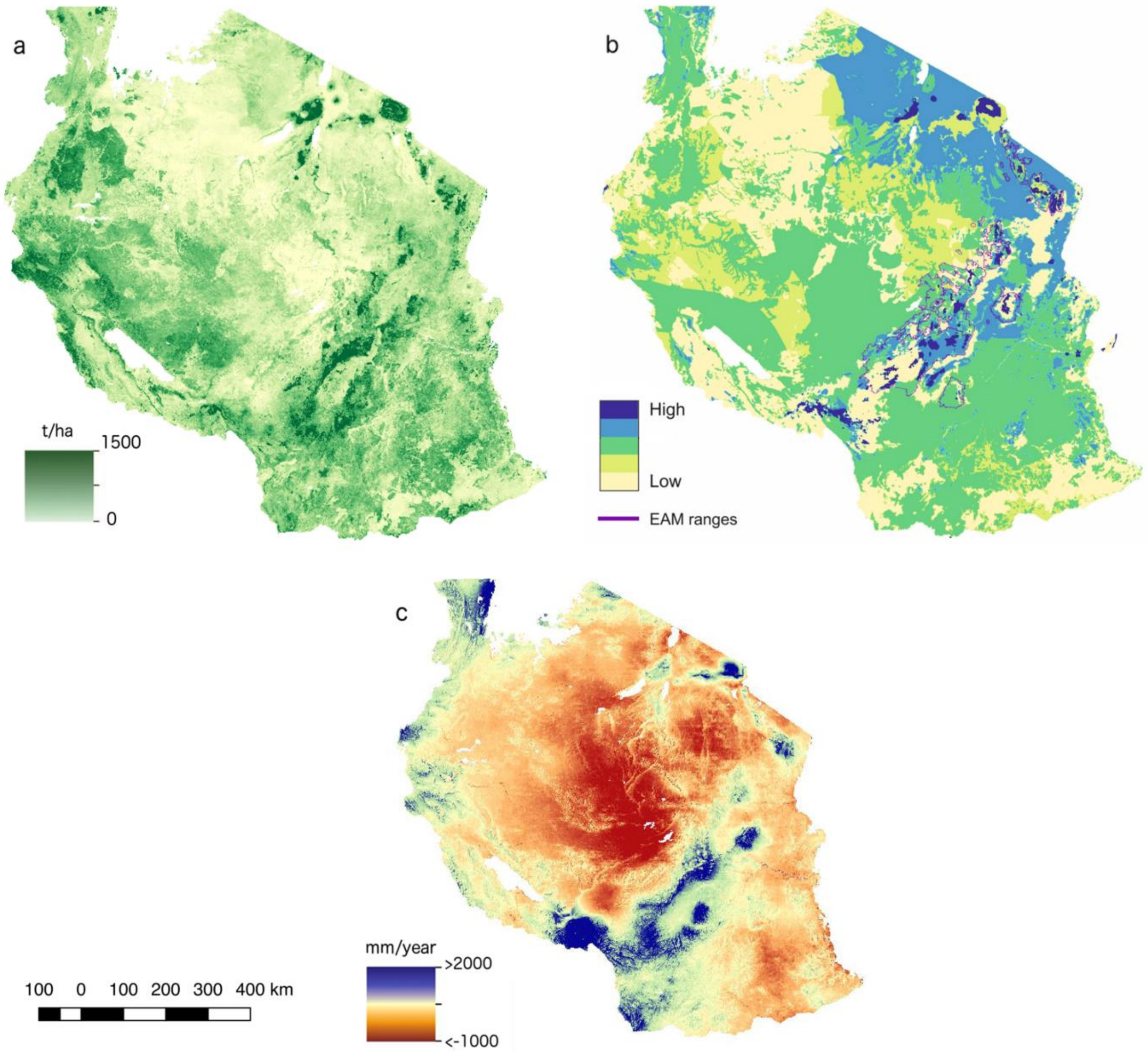

Figure S2 - Baseline maps for total carbon stock (a, ton ha^{-1}), biodiversity richness and rarity index of terrestrial vertebrates (b, range between 0 and 0.89) and water yield (c, mm $year^{-1}$) in Tanzania mainland. In b) the Eastern Arc Mountains biodiversity hotspot boundaries are represented by the purple line.

The high resolution adopted for the scenario analysis was helpful in incorporating local knowledge collected during the regional workshops, e.g. for simulating local patterns of small forest patches encroachment. To transfer the local representativeness of change pressures into the national scale impacts assessment on carbon and non-carbon benefits, we altered the spatial resolution of the layers used to calculate carbon stock, biodiversity and water yield change, in order to match the ca. 100-m scenario resolution. Then we generalised the results at 1-km resolution. This double resampling process has determined a loss of accuracy in the analysis.

For biodiversity and water yield, the downscaling of the original input datasets at the scenario resolution was applied to match the reference habitat types and land cover classes with those used for the scenario analysis. Then the biodiversity and the water yield indices and their changes were calculated at 1-km resolution.

For carbon stock, the biomass and soil carbon stock layers were downscaled from ca. 250 to ca. 100 m resolution, to apply the change pressure on biomass and land determined by the specific land change expected in the scenarios (e.g. form forest to cultivated land, from closed woodland to bushland). Then changes were aggregate at 1-km resolution. The total amount of carbon biomass removed is upper limited by land and biomass demand set for the scenarios. However, the pixel-base allocation for the carbon stock change is influenced by the pixel-base carbon density, particularly for soil stock, and therefore is affected by the resampling process.

1.3 Biodiversity richness and rarity index

The Biodiversity richness and rarity index in the baseline $BRRI_{gt_0}$ was calculated for each grid-cell (g) by the formula:

$$BRRI_{gt_0} = \sum_{1}^{i} \left(\frac{ESH_{igt_0}}{ESH_{it_0}} \times R_i\right)$$

with ESH_{igt_0} the extent of suitable habitat of the *i* species in each pixel g, ESH_{it_0} the total extent of suitable habitat of the i species in Tanzania and R_i the ratio of the distribution range of the i species in Tanzania over the globe, at the time t_0.

Changes between the scenarios and the baseline where calculated for each pixel (g)

$$BRRI_g = \sum_{1}^{i} \left(\frac{ESH_{igt_1} - ESH_{igt_0}}{ESH_{it_0}} \times R_i\right)$$

with ESH_{igt} the extent of suitable habitat of the i species in each pixel g in the scenario (t_1) or in the baseline (t_0), ESH_{it_0} the total extent of suitable habitat of the i species in Tanzania in the baseline and R_i the ratio of the distribution range of the i species.

When calculating the BRRI changes in the future scenarios we assumed that:

- LULCC-sensitive species abandon habitats converted to cultivated land or degraded;

- non-LULCC-sensitive species lose habitat due to conversion to cultivated land (e.g species mainly associated with forest or closed canopy woodland or generalist species reported not to be tolerant to agriculture activities);

- non-LULCC-sensitive species mainly found in grassland can gain habitat following degradation of woodland and bushland, when degradation is above 15m^3 ha^{-1} wood biomass loss.

These rules are based on the reported habitat preference for the species[ii], on the reference land use and land cover classes, and on the biomass changes calculated for the scenarios; gains are considered only within the extent of occurrence of each species. We did not consider other factors than habitat that could affect species capacity of moving or adapting to changes.

The adopted biodiversity richness and rarity index (BRRI) has the advantages of being calculated from data relatively easy to obtain on a large scale, and of being directly sensitive to LULCC, compared to other quantitative indices (e.g. species abundance, richness, diversity). However, it doesn't consider multiple aspect of biodiversity complexity, e.g. functional or taxonomic diversity, connectivity, complementarity, species adaptation capacity. In Tanzania the BRRI represents well the highly endemic montane forests and species-rich woodlands, and particularly emphasized the impacts of habitat changes on rare species. Using other indices, or other prioritisation approaches, different spatial pattern would emerge, e.g. weighting all species equally as in the species richness index.

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[i] Tatem, A. J. (2017) WorldPop, open data for spatial demography. Sci. Data 4:170004 doi: 10.1038/sdata.2017.4

[ii] IUCN 2016. The IUCN Red List of Threatened Species. Version 2016-3. Downloaded 05/2016. [www datset]. URL http://www.iucnredlist.org.