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ORIGINAL ARTICLE

# Exploring future agricultural development and biodiversity in Uganda, Rwanda and Burundi: a spatially explicit scenario-based assessment

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**Abstract** Competition for land is increasing as a consequence of the growing demands for food and other commodities and the need to conserve biodiversity and ecosystem services. Land conversion and the intensification of current agricultural systems continues to lead to a loss of biodiversity and trade-offs among ecosystem functions. Decision-makers need to understand these trade-offs in order to better balance different demands on land and resources. There is an urgent need for spatially explicit information and analyses on the effects of different trajectories of human-induced landscape change in biodiversity and ecosystem services. We assess the potential implications of a set of plausible socio-economic and climate scenarios for agricultural production and demand and model-associated land use and land cover changes between 2005 and 2050 to assess potential impacts on biodiversity in Uganda, Rwanda and Burundi. We show that different future socio-economic scenarios are consistent in their projections of areas of high agricultural development leading to similar spatial patterns of habitat and biodiversity loss. Yet, we also show that without protected areas, biodiversity losses are higher and that expanding protected areas to include other important biodiversity areas can help reduce biodiversity losses in all three countries. These results highlight the need for effective protection and the potential benefits of expanding the protected area network while meeting agricultural production needs.

**Keywords** Scenarios · Land use model · Biodiversity · Trade-offs

## Introduction

The global human population is projected to reach 9 billion by 2050 and already, for one in six people, current agricultural production is not able to fulfil basic dietary needs (Godfray et al. 2010).The increased need for food (a projected rise of 70 % by 2050) will be exacerbated by increasing prosperity in some regions which will be associated with increased demand for protein (Alexandratos 2009). This rising demand represents an enormous need for increased agricultural production. Between 1965 and 2005, increases in production similar to what is needed by 2050 have been achieved with only a 12 % increase in global

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cropland area, largely through improved crop breeding and agricultural intensification (Foley et al. 2005). However, this increased agricultural production has come at a cost: 30 % of agricultural lands globally are now degraded, and annual increases in cereal crop yields in the major 'bread-basket' regions are slowing (Foley et al. 2011).

Further intensification and expansion of land use for the production of agricultural commodities will likely reduce our ability to maintain biodiversity and ecosystem services. The trade-offs are poorly understood in absolute terms and with respect to spatial extents, but essential for decision-makers to balance different demands on land. Sub-Saharan Africa has huge potential to increase food production through productivity increases and agricultural expansion (Alexandratos 2009). The highest impacts from agricultural transformation on biodiversity will likely occur in areas combining high population densities and high biodiversity values. Uganda, Rwanda and Burundi currently have population growth rates of between 2.7 and 3.3 % which is well above the world average of 1.3 % (African Development Bank 2014). A large proportion of the population live on less than US$1.25 per day: from more than 80 % in Burundi to almost 40 % in Uganda (World Bank 2014). Yet, GDP in the region is projected to increase by 6–7 % in 2015 (African Development Bank et al. 2014). The importance of the agricultural sector in national economies is decreasing, while the contribution of the services sector, and in Uganda the industrial sector, is increasing (World Bank 2015). Agricultural productivity will need to increase to feed the rapidly growing population and meet changing consumption patterns that come with increased wealth such as increased demand for meat products (e.g. Aiking 2011). These increases in demand are likely to lead to expansion of agricultural land (Delzeit et al. 2016). Since the region is also the most ecologically important in Africa (BirdLife International 2012; CEPF 2012) achieving food security in these countries could have devastating results for the region's high biodiversity values. How governance challenges in East Africa develop will be an important determinant of whether and how such trade-offs between future food security and biodiversity are tackled (Guillaume and Stasavage 2000; Mandemaker et al. 2011). Potential future trade-offs between agricultural expansion and biodiversity have been studied at global and regional scales (Seppelt et al. 2013), e.g. Delzeit et al. (2016) analyse global cropland expansion and potential impacts on biodiversity under different global scenarios, and Biggs et al. (2008) studied biodiversity changes under the Millennium Ecosystem Assessment scenarios in Southern Africa. In this study, we use a novel interdisciplinary framework consisting of a set of plausible regionally developed socio-economic scenarios, models and biodiversity assessment methods to assess the potential impacts of increased agricultural production on biodiversity in Uganda, Rwanda and Burundi. We also assess the potential of different conservation policies to help maintain biodiversity while meeting demands for food production.

## Methods

### Study region

Our study region covers Uganda, Rwanda and Burundi. The region contains 45 key biodiversity areas (KBAs) and very high levels of species richness and endemism, particularly along the mountains of the Albertine Rift (Plumptre et al. 2007). A total of 747 protected areas overlap with the region, covering 16 % of Uganda, 10.5 % of Rwanda and 4.8 % of Burundi.

### Scenarios

Scenarios of change for the East Africa region are based on a regional scenarios development process led by the CGIAR Climate Change, Agriculture and Food Security (CCAFS) programme. A set of four socio-economic scenarios were developed for East Africa through four stakeholder workshops in 2010 and 2011 (Vervoort et al. 2013). A total of 120 stakeholders from Kenya, Tanzania, Ethiopia, Uganda, Rwanda and Burundi as well as regional and global actors from a wide range of sectors including government, private sector, regional governance bodies, academia, media and CSOs were involved in the scenario development process. To create the scenarios, participants first identified a list of key drivers for the future of the region, including economic, governance, environmental and other dimensions. Then, participants voted on which drivers were considered not only highly important for future food security, rural livelihoods and environmental change, but also highly uncertain—i.e. drivers could develop in strongly different future directions. Some drivers, like population growth, were considered highly important, but not highly uncertain. Climate change was also considered highly important, but it was not considered useful to explore scenarios with no climate change—as climate adaptation was part of the focus of the project, and climate uncertainty was better explored through model inputs than as an axis of uncertainty in the basic scenario framework. Following such considerations, the two drivers of change for food security, environments and livelihoods that the workshop participants considered to be most relevant as well as uncertain were: regional integration and mode of governance, reflecting stakeholder perspectives that such governance aspects would play a key role in determining East Africa's future. For each of these two drivers, two extreme states were considered: "integrated" and "fragmented" region and "proactive" and "reactive" governance. Their combination provided the basis for the following four scenarios: high regional integration with proactive governance (S1: industrious ants), high integration with reactive governance (S2: herd of zebra), fragmented and proactive governance (S3: lone leopards) and finally fragmented and reactive governance (S4: sleeping lions).

The four storylines were developed by looking backwards from the four future worlds represented by the combinations of drivers and their states, and by determining the steps required to go from these futures back to the present world. In the process, many other drivers were added to inform the scenario narratives. Two drivers of change in the region that were considered highly relevant but very likely were population growth and climate change (increase of 2 °C and increase in climate variability; Dufresne et al. 2013). A full summary of the four scenario narratives is provided in Online Resource 1.

After developing the storylines, the participants evaluated the importance and direction of change in a number of key drivers such as population, GDP, technology impacts on yields and farm input costs for each scenario. In addition, volatility of these drivers was discussed. This semi-quantification of drivers supported the subsequent full-quantification of the scenarios.

## IMPACT model

The scenarios were further quantified with the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) partial equilibrium model (Rosegrant et al. 2008). IMPACT provides annual estimates of crop and livestock production demands, technological-based yield changes and population developments at national scales throughout the modelling period of 2005–2050. Population projections are adapted from projections of the Shared Socio-economic Pathways (O'Neill et al. 2014). IMPACT incorporates the global context through international trade and the interplay of global supply and demand of agricultural commodities. The model distinguishes between rainfed and irrigated cropping systems; however, for the analysis in this study, we only used results for rainfed production systems as these have a greater impact on agricultural extensification and make up more than 90 % of the production in our study area. The four scenarios were implemented with climate change projections from the IPSL[1] General Circulation Model (GCM) under the RCP 8.5 (Riahi et al. 2011) emission pathway as well as a constant climate reference scenario. Figure 1 shows the changes in population and GDP under each of the four scenarios for the three study countries.

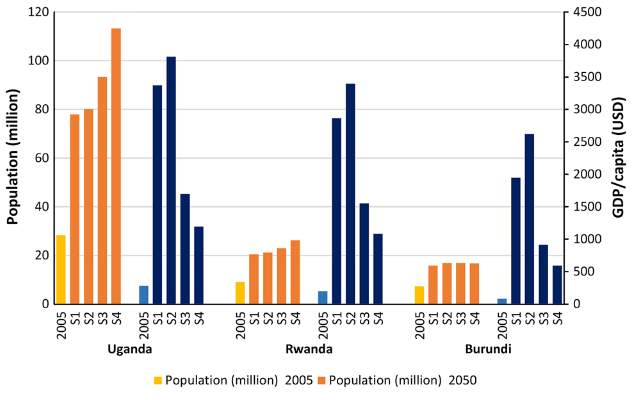

**Fig. 1** Projected changes in population and GDP for four socio-economic scenarios for Uganda, Rwanda and Burundi (2005–2050)

## LandSHIFT model

We used the spatially explicit, integrated land use model LandSHIFT (Schaldach et al. 2011) to simulate land use and land cover change for a baseline (2005) and future (2050) period at a spatial resolution of 30 arc seconds (~1 km). LandSHIFT has been applied successfully in Africa in previous studies (Alcamo et al. 2011; Heubes et al. 2013). The model allocates land use to grid cells based on a weighted multi-criteria analysis which calculates potential suitability for the land use activities urban, crop and livestock. The model was initialised with the GLC2000 land cover dataset (Bartholomé and Belward 2005). This dataset provides high-resolution (30 arc seconds), harmonised land cover for the globe based on satellite remote sensing data from the SPOT-4 VEGETATION sensor. GLC2000 is widely used in studies requiring spatially explicit land use information and is regarded to be a good representation of land use in the year 2000 (Fritz et al. 2011) with particularly good validation results for the East Africa region (Herold et al. 2008).

Baseline crop areas and crop yields for the study region were obtained from FAO (2014) statistics using a mean for the period 2004–2006 with future values derived from the IMPACT model results. Crop yields were scaled spatially using crop yield simulations from the LPJmL crop model (Bondeau et al. 2007). Other input datasets in the LandSHIFT model are terrain slope (SRTM; Jarvis et al. 2008), population density (GRUMPv1; CIESIN et al. 2011) and road network (gROADSv1; CIESIN and ITOS 2013). LandSHIFT outputs all land cover types from the baseline land use dataset and sub-divides arable land classes into 12 different crop classes. All model runs for LandSHIFT include projections of climate change based on the RCP 8.5 emission scenario as a driver for the LPJmL crop model in line with the projections of demand and production produced by the IMPACT model.

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[1] IPSL-CM5A-LR—The Institut Pierre Simon Laplace's Earth System Model.

### Assessing biodiversity changes

We assessed changes in biodiversity resulting from land use and land cover changes using a metric of relative biodiversity which is based on the distribution of suitable habitat for species in the region. This method allows for the assessment of potential impacts on biodiversity for the whole study region, as well as an evaluation of the within-region variability of these impacts. The metric is adapted from the impact score used by Buchanan et al. (2011) and uses all available species extent of occurrence (EOO) data for the study region from the IUCN Red List for vertebrate classes (IUCN 2013) that have been comprehensively assessed, i.e. birds, amphibians and mammals (1483 species in the study region). The suitable habitat for individual species is based on a crosswalk table between LandSHIFT land use types (adopted from GLC2000 land cover classes) and IUCN habitat classes, which are based on expert opinion and the literature and was originally developed by Foden et al. (2013). A species is counted as being present in a given $\sim 10 \times 10$ km grid cell if its EOO overlaps with a grid cell and if that grid cell contains suitable habitat (i.e. land cover). The biodiversity metric of a grid cell for a given time period is the area of the grid cell where a species is present divided by the total area of grid cells in the study region where the species is present. This figure is then multiplied by the ratio of the area of overlap of the species' EOO with the study region to its total (global) EOO area. This aims to account for the range of the species outside the study area, giving a higher weighting to species with a small EOO. The individual species scores are then summed over all species to obtain a total biodiversity value. Changes in the biodiversity metric as a result of land use change are assessed for each species and grid cell relative to the baseline situation.

### Assessing impacts of conservation policy

To assess spatial trade-offs between different conservation policies and agricultural production, the LandSHIFT model was driven with different assumptions with regard to protected areas (PAs) using data from the World Database on Protected Areas (WDPA) (IUCN and UNEP 2014) and key biodiversity areas (KBAs) (BirdLife International 2013). The model experiments analyse three different assumptions: land conversion possible in PAs ("PA on"), no land conversion possible in PAs ("PA off") and a maximum protection assumption where no land conversion is possible in PAs and KBAs ("PA + KBA"). We present the main land use change results only for the baseline "PA on" assumption under each scenario. For comparison, changes in extent and location of forest cover (defined as all forest land use classes in LandSHIFT) as well as changes in biodiversity using the biodiversity metric are presented for all three assumptions under each scenario, even though the different scenario narratives support different assumptions. Under S1: industrious ants, there is likely effective protection of PAs, while under S4: sleeping lions, land conversion in PAs is more likely.

## Results

### Key agricultural changes

Crop yields, which are driven by technological improvements and climate change and crop production—driven by population and demand—for nearly all modelled crops, are projected to increase for all scenarios and countries (key crops shown in Fig. 2), but there are clear differences between the scenarios. For instance, yield and production are almost always highest under S1 and lowest under S4.

### Crop yields

Differences in crop yields among the scenarios are the result of different assumptions on the levels of technological improvements in farming methods in the scenarios. For example, in the S1 scenario, investments in new technologies and practices favour staple foods for regional consumption, while in the S4 scenario, technological investment favour export crops. Apart from exogenous assumptions on technological improvements, crop yields also respond to changes in commodity prices, and these prices in turn can be affected by climate change.

### Crop production

Under all scenarios, production increases are greatest for relatively recently introduced cash crops such as vegetables in all three countries and rice in Burundi and Rwanda. Coffee is a traditional cash crop in all three countries.

#### *Meat production*

Under all scenarios and for all countries, the national demand for meat products in 2050 is much higher than production, even though production increases between 39 % (S4) and 116 % (S1) across the four meat products (beef, lamb, pork and poultry) (Fig. 3). Feed demands are driven by livestock production and the availability and prices of other feed types. Livestock production is determined by animal numbers and animal yield. Animal numbers are determined through animal population dynamics, and economic responses to changes in animal products, and feed prices. Animal yields are determined by exogenous scenario assumptions on

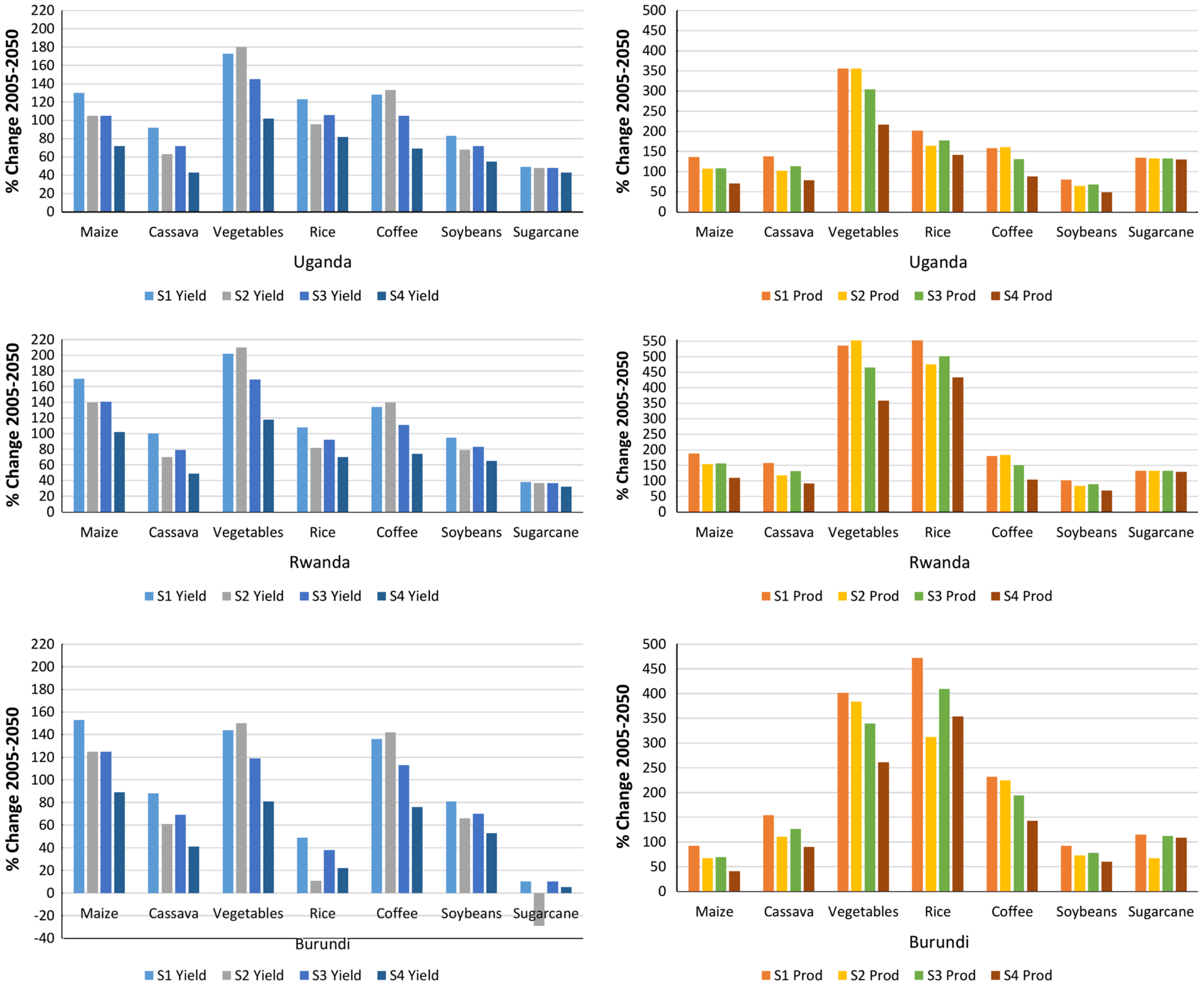


**Fig. 2** Changes in yields and production (% change between 2005 and 2050) for key crops under the four scenarios for Uganda, Rwanda and Burundi with impacts of climate change under the RCP 8.5 emission pathway

animal yields. This results in productivity increases for all four meat products considered in the model in scenarios S1 and S2. In S3, there are low, and in S4, no changes in livestock yield in the modelled period.

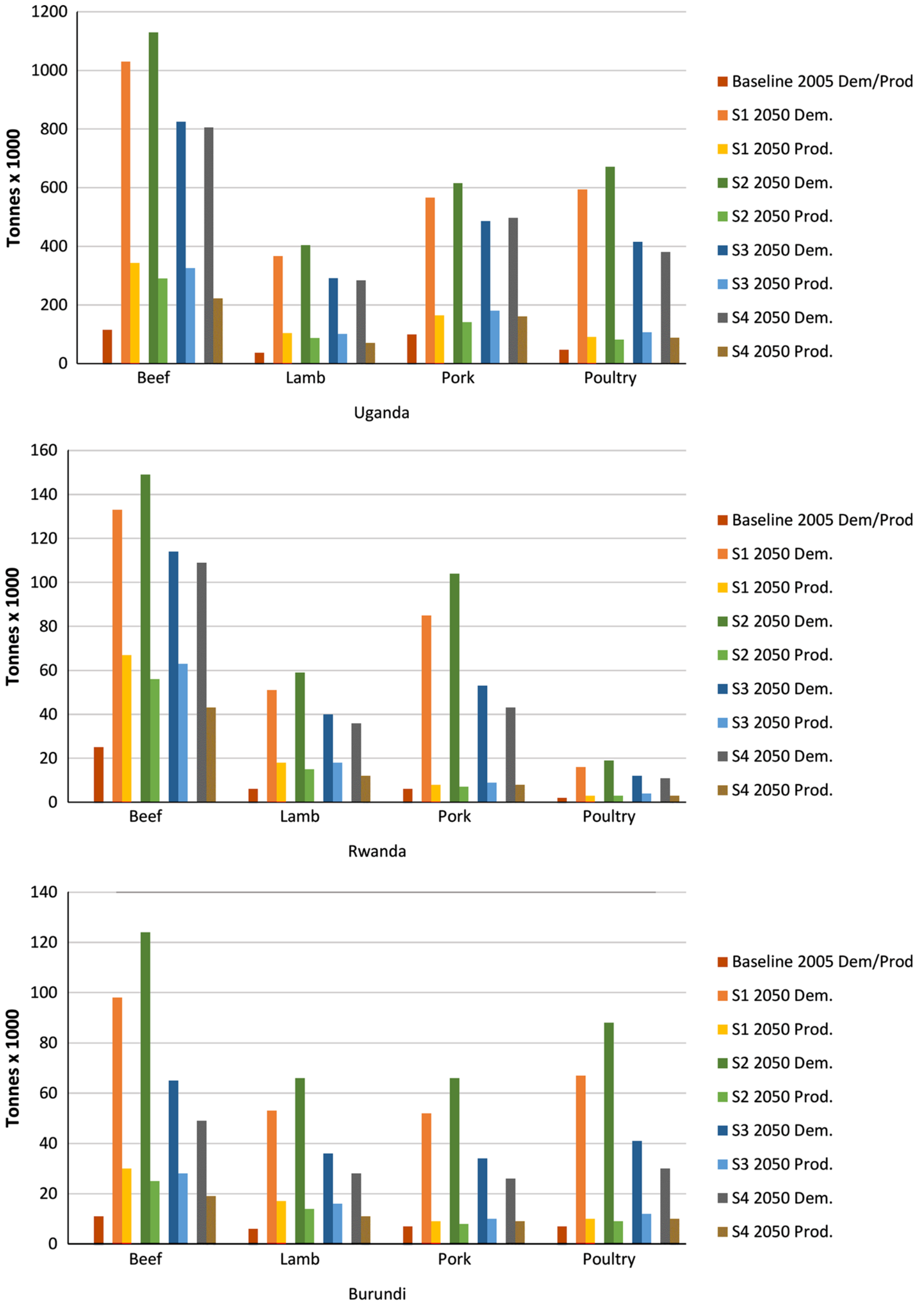
## Changes in land use and land cover

Under all scenarios, projected land use and land cover changes result in considerable expansion of cropland and grazing land in Uganda and Burundi. This expansion is the main driver of loss of natural grassland, shrubland and forest (Fig. 4). Most deforestation is projected to occur in Uganda, primarily in the north and west of the country (Fig. 5). Between 2005 and 2050, a total of between 27,602 km$^2$ (33 %) (S1) and 65,908 km$^2$ (79 %) (S4) of forest is projected to be lost in Uganda. In Burundi, up to 5614 km$^2$ (90 %) of forest is lost under S4.

Crop and pasture lands are projected to decrease in Rwanda, and forest loss is expected to be relatively low, but these changes will be exclusively driven by a large urban expansion (from 98–647 km$^2$ under S4). In the LandSHIFT model, allocation of urban areas is driven by population growth and takes precedence over any other land use type. In Rwanda, urbanisation takes place mainly in the centre of the country and on the shores of Lake Kivu. In Uganda, where the greatest absolute increases in urban area are expected to take place, strong urban development is expected on the shores of Lake Victoria (Fig. 5).

Changes in livestock systems drive the expansion of pasture areas as well as grazing densities (livestock units/ha). Pasture areas expand in both Uganda (18,427–18,735 km$^2$) and Burundi (4423–4725 km$^2$) with little difference between scenarios. Cropland

**Fig. 3** National demand and production for meat products for 2005 baseline and in 2050 for each scenario and country



expansion in Uganda and Burundi is greatest under S4, where GDP per capita is lowest and population growth strongest (Fig. 1).

## Biodiversity changes

Projected relative loss of biodiversity can be observed for large areas under all scenarios and in all three countries. The largest decreases are found in the Albertine Rift along Lake Kivu in Rwanda and Lake Edward in south-west Uganda where biodiversity importance is highest in the baseline situation (Fig. 6). Also, large areas along Lake Victoria in Uganda lose biodiversity due to urbanisation and conversion to cropland. Overall, Burundi is projected to incur the greatest losses of biodiversity by area: 82–87 % of the country loses biodiversity under scenarios S1 and S4, respectively. Both Uganda and Rwanda lose biodiversity in 24–30 % of their total land area under these same scenarios.

The spatial patterns are very similar among scenarios, although in scenarios S3 and S4, more area (3 % on average between S1–S2 and S3–S4) is impacted and the magnitude of impacts in cells that lose biodiversity is generally greater. This is the case in particular along a south-west to north-east corridor across Uganda (Fig. 6).

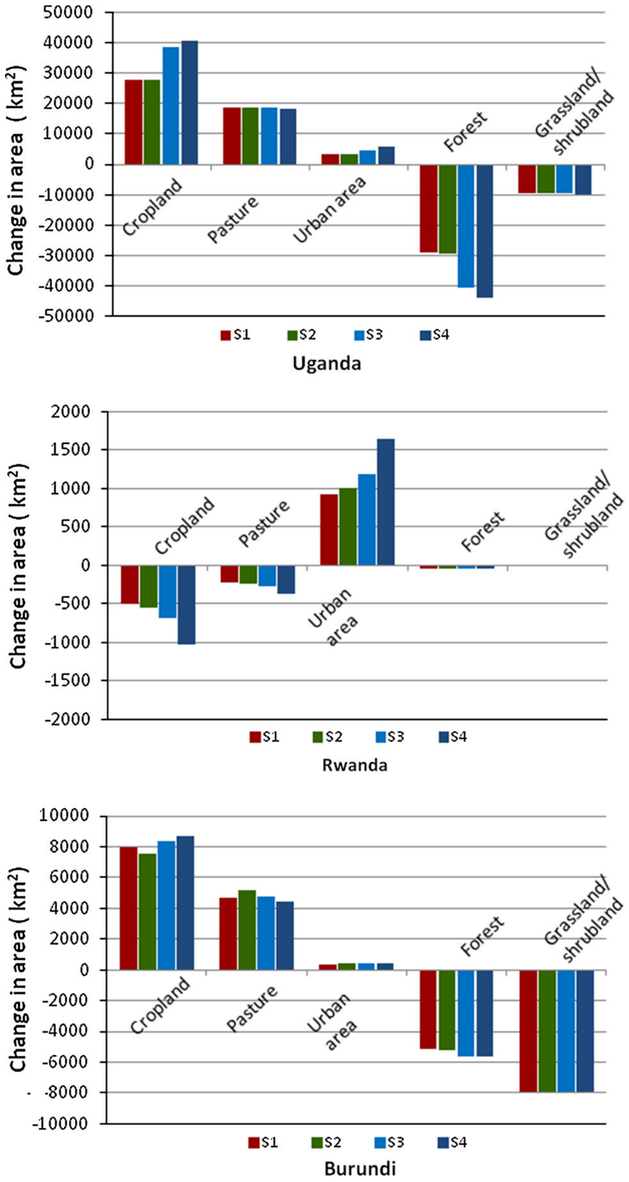


**Fig. 4** LandSHIFT modelled changes in area (km$^2$) of major land use classes in Uganda, Rwanda and Burundi for four socio-economic scenarios between 2005 and 2050. Protected areas are assumed to remain unconverted. Note the different scales of the *y*-axes

## Impacts under different conservation policies

In Uganda, a total area of 36,018 km$^2$ (14.8 % of the country) has a protected area status according to the WDPA, whereas in Rwanda, only 2691 km$^2$ is protected (10.6 %) and 1309 km$^2$ in Burundi (4.8 %). Mean modelled forest cover in the baseline year of 2005 in these protected areas is between 38 % (Burundi) and 42 % (Rwanda). Allowing for land use changes within protected areas (PA off) results in the degradation of habitats within these areas and differences in the location of impacts on forest and biodiversity loss between scenarios (Online Resource 1, figures S5 and S6).

### *Forest loss*

Under the assumption that conversion of protected areas is allowed (PA off), between 22 % (S1) and 34 % (S4) of forest is lost within these protected areas in Uganda (Online Resource 1, table S4), while nearly all forest in protected areas is lost in Rwanda and between 86 % (S1) and 100 % (S3 and S4) in Burundi. Under the maximum protection assumption (PA + KBA), whereby protected areas and currently defined key biodiversity areas are protected from conversion in the model, there is slightly more forest loss overall in Uganda under all four scenarios compared to no protection. In Rwanda and Burundi, maximum protection leads to less forest loss under all scenarios with a maximum of 6.1 % (Rwanda) and 72 % (Burundi) of forest loss (compared to 100 % forest loss in both countries under the PA off assumption). Spatially, under a maximum protection assumption for the S1 scenario, more forest is lost towards the north of Uganda and south Burundi, while without any protection (PA off), more forest is lost in protected areas along the rift valley (Online Resource, figures S3, S4 and Fig. 5). In the LandSHIFT model, urban areas can expand into protected areas, even under a no conversion (PA on) assumption in the model if population densities are high in the baseline situation. Urban expansion leads to some small losses of forest (up to 2.2 % in Burundi) in protected areas, particularly under those scenarios where population pressure is high (S3 and S4).

### *Biodiversity loss*

Biodiversity losses under a no protection assumption (PA off) are much higher for all three countries. Particularly in Rwanda, where total loss of biodiversity by area increases up to 161 % compared to losses with effective protection (PA on) (Online Resource, table S5). For Uganda, this increase is between 46 % (S1) and 63 % (S3) and in Burundi between 4 and 35 % for scenarios S2 and S3/S4, respectively. In contrast, total area of biodiversity loss under a maximum protection assumption (PA + KBA) is reduced for all three countries and under all scenarios, with as much as 91 % for Rwanda, compared to the PA on assumption. Spatially, the broad-scale patterns under each scenario are similar, with large areas of Burundi and the north of Lake Victoria most affected. However, under a maximum protection assumption (PA + KBA), there are no biodiversity losses in the KBA network, which is particularly important for the Albertine Rift valley in all three countries where current biodiversity values are highest (Fig. 6).

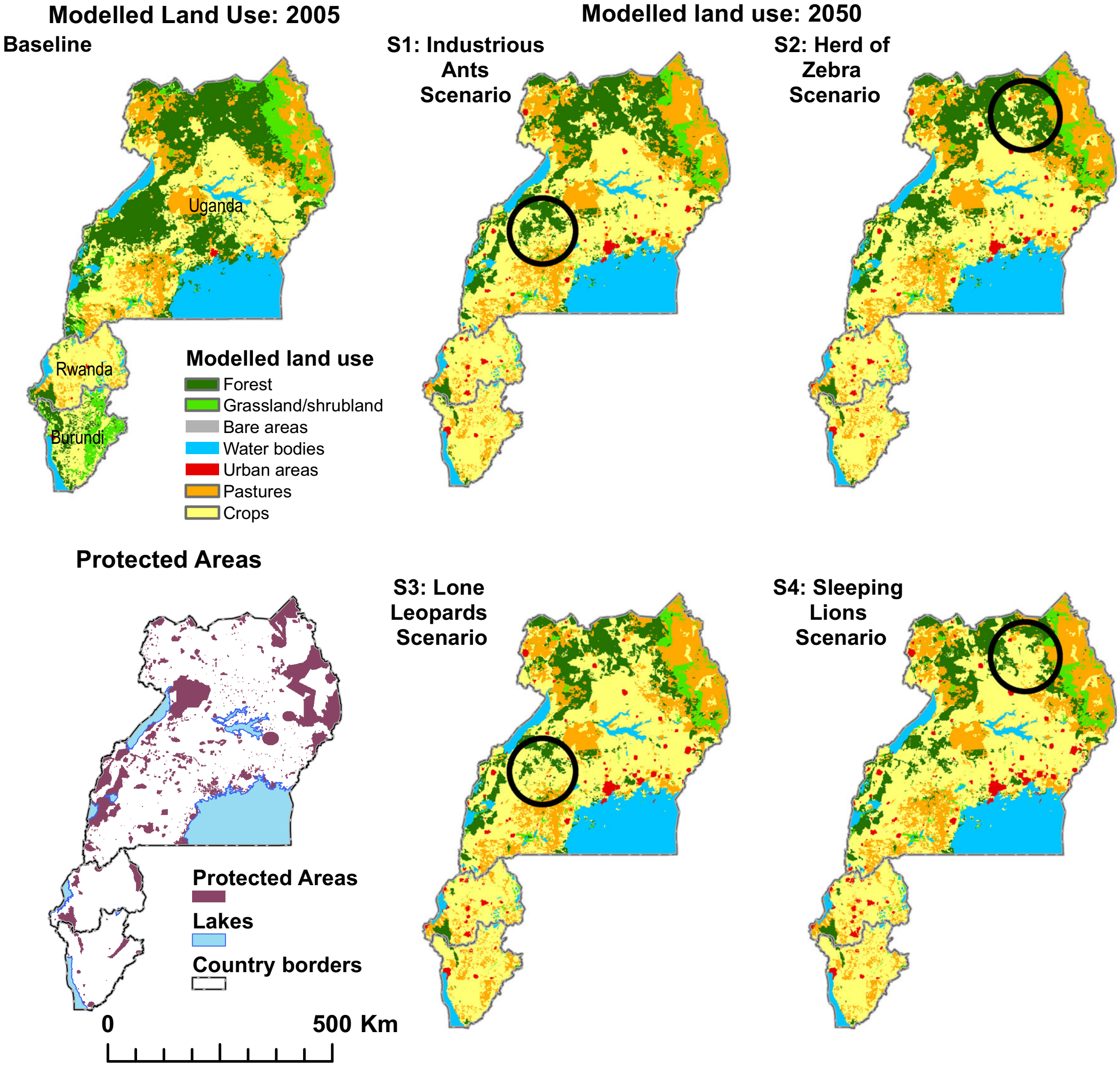


**Fig. 5** Modelled land use in 2005 and projections for 2050 for four socio-economic scenarios for Uganda, Rwanda and Burundi. Protected areas are assumed to remain unconverted. Black circles highlight key areas of change and differences between the scenarios

## Discussion

### Socio-economic pathways and land use change

In our analysis, the socio-economic pathways are expressed in the IMPACT model in terms of differences in the changes in crop yields and in agricultural production—driven by population and demand, which is also a function of GDP per capita. All scenarios assume rapid population growth and further land conversion, as realistic alternative pathways are currently not available.

In the S1 scenario with an integrated and cooperative region and pro-active governance supporting staple foods production and regional trade, population projections for 2050 are the lowest, but GDP is more than twice that of the S2 scenario, where action on food security and livelihoods is limited, and economic growth policies lead to vulnerability to global market forces and environmental degradation and so less GDP growth than under S1 in the longer term. IMPACT assumes that increases in wealth, expressed as GDP per capita, lead to increased demand for animal protein and thus the scenarios with greatest increase in GDP show the greatest increase in demand for meat products (Figs. 1, 2), which is consistent with other studies (e.g. Aiking 2011). Under the S4 scenario, population projections are highest, and GDP per capita lowest. Poorer people eat less, particularly meat products, than wealthier people (Valin et al. 2014), which explains why the increase in demand for meat products is lowest under S4 in all three countries. Crop production still increases under this scenario compared to 2005 though, but less so than under the other scenarios. In Uganda and Rwanda, for example, even though population is highest under S4, crop production does not follow suit because GDP per capita is at its lowest. Other factors such as a lack of resources (e.g. land and inputs) to be able to meet the demand also play a role as yields are also lowest under the S4 scenario.

Overall, crop production increases the most under the S1 and S2 scenarios for all three countries, but cropland expansion is lowest for these two scenarios due to the greater increase in yields. The scenario demands for crops cannot be satisfied from agricultural intensification and extension of cropland in Burundi and Rwanda due to land constraints in the model by 2040. Even with the conversion of existing PAs, around 2.40 and 3.37 million tonnes of crop demands would additionally need to be imported by 2050 for the S1 scenario and around 2.82 and 3.38 million tonnes for the S4 scenario. Strict conservation of PAs and KBAs causes production deficits for Burundi and Rwanda of 3.52 and 5.88 million (S1) and 3.63 million tonnes and 5.62 million tonnes (S4), respectively. Future crop demands in Uganda can be satisfied without conflicting with the conservation of PA and KBA areas as there is enough natural land available for conversion.

While most modelled land conversion in the region is the result of cropland expansion, increases in livestock production also leads to conversion of large areas of natural land to grazing land. However, as a result of climate change, pasture yields are projected to increase. Higher grazing intensities on more productive pastures can help limit the expansion of pasture land. Similarly, crop yields tend to benefit from the projected climate change in the region, and therefore, the area required to satisfy the increase in production demands from population or GDP

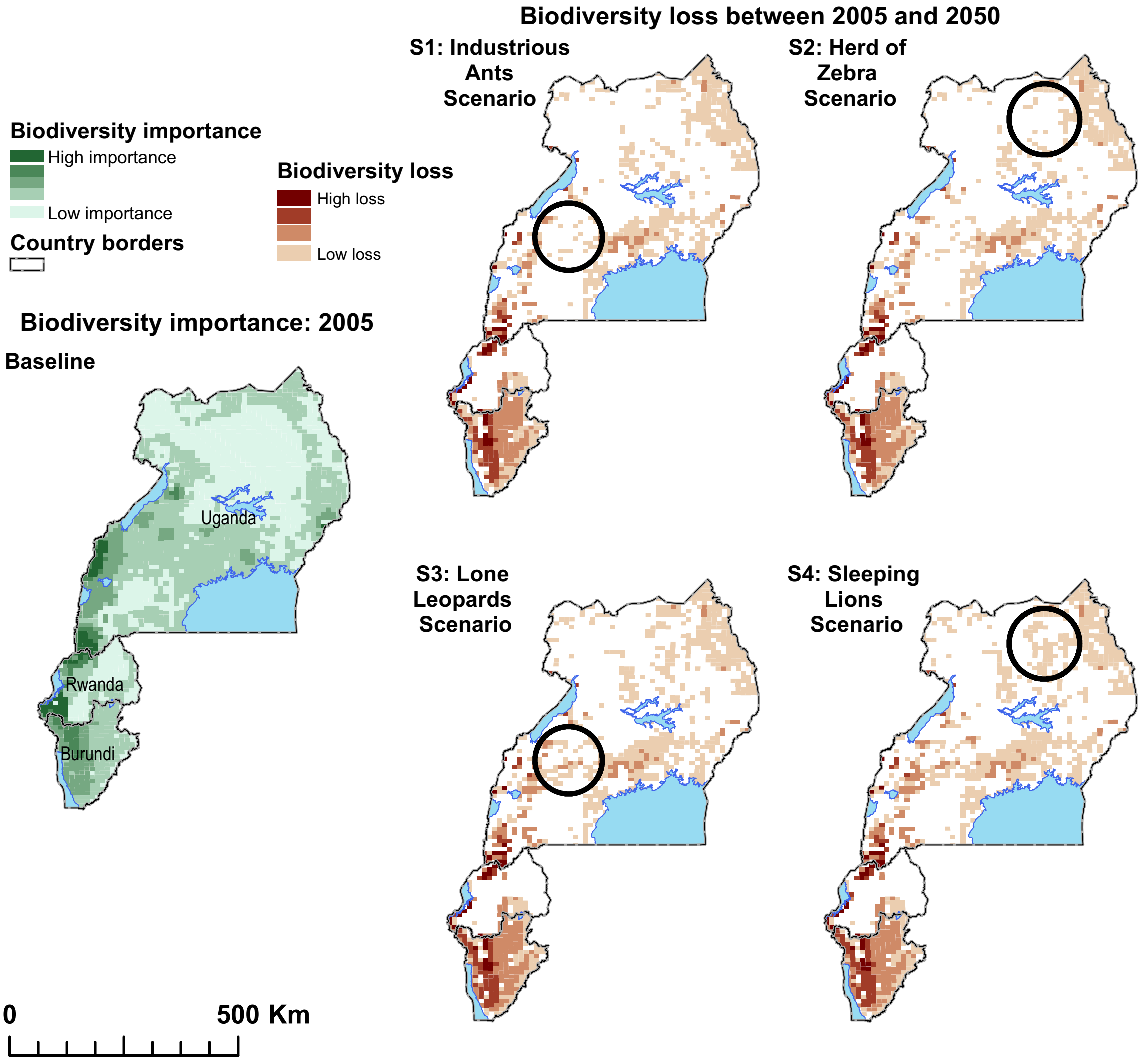


**Fig. 6** Current biodiversity and projected changes in biodiversity between 2005 and 2050 for four socio-economic scenarios of change for Uganda, Rwanda and Burundi. Protected areas are assumed to remain unconverted. *Black circles* highlight key areas of change and differences between the scenarios

increases is reduced. The choice of climate scenario for this analysis likely influences these findings. The RCP 8.5 emission pathway used in this analysis has a small negative effect on yield of most crops in this region, but because other regions are projected to be affected to a much greater degree, global prices for these crops increase, incentivising farmers everywhere to increase production. In the study region, this endogenous price effect on farmers was larger than the biophysical shocks supplied by the crop models, resulting in overall positive impacts on yields. Simulations with different RCP pathways lead to overall smaller yield increases in this region (Vervoort et al. 2013) and therefore to even higher demands for agricultural land under each of the four socio-economic scenarios.

Changes in agricultural production are driven by domestic and global demands with the allocation of agricultural areas based on accessibility and suitability. Expansion and intensification of agricultural production can be achieved under different agricultural systems which react to different policy and socio-economic triggers. Small-scale mixed farming is the main agricultural system in this region. Large-scale industrial agriculture is still rare, but governments are looking to increase investments in, for example, biofuels (Mapendembe and Sassen 2014). However, this work does not capture differences in scales of farm development. Large-scale industrial agriculture may develop in areas that do not correspond to those areas considered most suitable in LandSHIFT and under rain fed conditions, as such players may address these constraints by constructing crop irrigation schemes and roads. Therefore, this may lead to different impacts on biodiversity.

## Impacts on biodiversity

The projected impacts on biodiversity from land use change under the four scenarios are expressed through changes in species' suitable habitat. Relative losses are greater in areas with current high values of biodiversity as changes in habitat in those regions impact more species. While the analysis has focused only on species losses, certain species are likely to gain from land cover changes. Particularly, generalist species will benefit from increased food availability in agricultural landscapes (Watson et al. 2013). However, for species with limited ranges, loss of habitat may lead to extinction (Purvis et al. 2000). The projected loss of pristine habitat in high biodiversity areas in the Albertine Rift is therefore of particular concern as this region is known to support many endemic species (Seimon and Plumptre 2012).

Habitat fragmentation can lead to considerable added pressure on species (Andren 1994), but such effects are not fully accounted for at this resolution. Nevertheless, this analysis at the regional scale is able to highlight those areas most likely under threat from agricultural development and can thus be used to guide further detailed impact studies on the effects of local fragmentation. In addition, since biodiversity losses are assessed within spatial units of $\sim 10 \times 10$ km, small habitat losses within cells do not necessarily lead to a loss of biodiversity as long as some habitat remains, as it is assumed species will be able to utilise that remaining habitat. Therefore, small-scale land conversions do not always translate to loss of biodiversity which may lead to an underestimation of the total impact of land conversion.

## Conservation trade-offs

Protecting PAs and KBAs from conversion can lead to perverse effects under certain conditions. Indeed, under this assumption, relatively more forest is projected to be lost overall in Uganda compared to when conversion is allowed, under all scenarios. This is because relative to the stock within these areas, more forest is lost outside their boundaries. Conversely, when there is little forest outside protected areas, their effective management generally has positive impacts on the maintenance of remaining forest. This is the case in Burundi and Rwanda where the current forest stock is mostly located in protected areas. This has important implications for conservation initiatives based on maintaining or increasing carbon stocks such as REDD + schemes. Such schemes and other conservation or land use planning initiatives need to take into account total stocks of resources, such as forests, their locations, the institutional arrangements they are managed under as well as projected changes in demands for land and forest products (e.g. Corbera and Schroeder 2011). Focusing forest conservation efforts only on those areas that are already protected may lead to increased deforestation elsewhere (Andam et al. 2008).

Differences in biodiversity impacts under different conservation policies are directly linked to trade-offs in expansion of agricultural area and loss of natural land. However, the greater projected loss of forest in Uganda under a maximum protection assumption (PAs + KBA) does not lead to a greater loss in biodiversity overall, even though more species have preferences for forest habitats. This is the result of greater species richness and higher endemicity in KBAs and thus lower impacts from forest loss elsewhere, which is compensated by maintaining much higher species richness and key habitat in KBAs. This means that further protection of areas currently defined as key biodiversity areas would be able to maintain even greater levels of biodiversity. However, since Rwanda and Burundi cannot meet future food production demands under current land availability, this would add further pressure on food security in these countries.

For simplicity, our analysis included all designation categories of the WDPA, which includes those that allow for sustainable use. Under IUCN category V, agricultural use is likely as this category protects cultural landscapes. Category VI PAs, where sustainable use is used as a means to achieve conservation, are common in the region, but agriculture is generally not permitted.

## Conclusions

The demand for crops and livestock products is the main driver of conversion of natural land in Uganda and Burundi, while in Rwanda, urban expansion is the key driver of change due to most land already being under agricultural use. Impacts of projected agricultural extensification and natural land conversion on biodiversity are visible around Lake Victoria in Uganda, most of Burundi and along the highly biodiverse Albertine Rift in Burundi and Rwanda.

This study found that a number of factors can limit the potential increase in area needed to meet the growing demands for food in Uganda, Rwanda and Burundi. The spatial variability in the impacts of climate change in the wider region, for example, can lead to overall positive impacts on yields in the study countries through price effects. Also, while demand for pasture areas is projected to increase in the strong growth scenarios, this study found that improved yields through technological changes have the capacity to limit this expansion. Therefore, sustainable agricultural intensification that is adaptable to climate change is necessary to realise the projected needs in production increases while avoiding further land degradation and limiting land conversion (e.g. Prett et al. 2011).

Spatial patterns of habitat and biodiversity loss due to projected agricultural development are consistent among different future scenarios in this study. This suggests that these are, indeed, areas most under threat from likely future agricultural development in the region. We show that effectively managed protected areas are an important strategy to maintain biodiversity and reduce losses in the face of increasing demands for agricultural land. In addition, we found that protecting remaining forested and other high biodiversity areas outside formally protected areas can help avoid conversion displacement.

Implementing scenario analysis in a spatially explicit manner in the context of land use change and biodiversity conservation allows for the assessment of trade-offs between different demands on land. Such analysis can help in spatial planning as well as conservation decisions while considering the pressures and likely future threats from increases in demands for food. Building on these activities, more work should be undertaken to ensure that such considerations are effectively incorporated into policy and decision-making in relation to food security, climate change adaptation and biodiversity conservation in Uganda, Rwanda and Burundi.

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