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

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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 on 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

1. 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 fulfill 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 1965-2005, increases in production similar to what is needed by 2050 have been achieved with only a 12% increase in global 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, whilst 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 whilst meeting demands for food production.

2. Methods

2.1 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.

2.2 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 program (CCAFS). 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 CSO's 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 of 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.

2.2 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 modeling 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.

<Figure 1>

2.3 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 (~1km). 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 & 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 & 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.

2.4 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

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

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 literature and was originally developed by Foden et al. (2013). A species is counted as being present in a given ~10 x 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.

2.5 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 regards to protected areas (PAs) using data from the World Database on protected Areas (WDPA) (IUCN&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.

3. Results

3.1 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 Figure 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 favor staple foods for regional consumption while in the S4 scenario, technological investment favor 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.

<Figure 2>

3.1.3 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) (Figure 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 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.

<Figure 3>

3.2 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 (Figure 4). Most deforestation is projected to occur in Uganda, primarily in the north and west of the country (Figure 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 5,614 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 km^2 to 1,647 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, urbanization 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 (Figure 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 (4,423-4,725 km^2) with little difference between scenarios. Cropland expansion in Uganda and Burundi is greatest under S4, where GDP per capita is lowest and population growth strongest. (Figure 1).

<Figure 4>

<Figure 5>

3.3 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 (Figure 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).

<Figure 6>

3.4 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 2,691 km^2 is protected (10.6%) and 1,309 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 Figure 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 (Figure 6).

4 Discussion

4.1 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 (Figures 1 and 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 million tonnes and 3.37 million tonnes of crop demands would additionally need to be imported by 2050 for the S1 scenario and around 2.82 million tonnes 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 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.

4.2. 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 ~10x10 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.

4.3 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 project 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, 2009). 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.

5. 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, whilst 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 whilst avoiding further land degradation and limiting land conversion (e.g. Pretty 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 whilst 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.

Acknowledgments

We would like to thank all participants of the scenario development process for their active contributions. This work was funded through a grant from the MacArthur Foundation with funding for scenario development provided by CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS).

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Figure captions:

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

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 RCP8.5 emission pathway

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

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

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

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 assumed to remain unconverted. Black circles, highlight key areas of change and differences between the scenarios

Online Resources. 1 Additional information on methods and additional results.

We thank both reviewers and the editor for taking the time to go through our manuscript and provide feedback. Based on these comments and suggestions we have made considerable improvements to the manuscript, taking into account the requirements of the journal on length of manuscript. Therefore some additions (and suggested figures) have been added to the supplementary information rather than the main manuscript. Please find our responses in bold below.

Reviewer 1

Reviewer #1: This is a well written and clear article. The authors have done an excellent job of describing the rather complex methods, using supplementary material as needed .. and indeed this answered most of my questions so well done! The authors have made an important contribution in linking scenarios that were largely narrative and data based to spatial mapping, using the LandSHIFT model. They take it one step further by translating the changes in land use and land cover to impacts on biodiversity, again using a solid, well documented method. The results are clearly presented. The discussion is excellent, and again all of my questions which arose while reading the methods and results were answered in the discussion section. This is a very nice piece and I recommend it for publication. I have only three minor requested revisions.

1. page 4, lines 12 and 13: please give a brief summary of the precipitation and temperature projections for East Africa that arise from the RCP 8.5 emissions pathway (perhaps in the supplementary table).. this is important I think given that you later show that crop and pasture yields increase in this region; you explain why but it would be good to present the actual projections in a table.

We have added more information on the projections under the RCP 8.5 pathway for the study region in the supplementary information. Under this scenario and for this GCM, temperature increases with nearly 3 Deg C and precipitation on average with 53 mm (+73% increase) for the region.

2. section 3.5: assessing impacts of conservation policy. Could you kindly discuss whether or not the assumptions you make about conservation policy are more or less consistent with the four CCAFS scenario narratives. You apply your 3 conservation scenarios across all four CCAFs scenarios but surely some are more aligned with one story than another?

We have altered the text to: "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 likely"

3. Section 5.4: this is too short to even mention here, I think. Either discuss why you did this in a bit more detail or delete. Right now it seems like an add on and the paper would be fine without it.

We agree with the reviewer and have removed this section from the manuscript.

Reviewer 2

Reviewer #2: Summary:

This manuscript investigated the impact of the socio-economic and climate changes on trade-offs between agricultural productions and biodiversity loss in Uganda, Rwanda and Burundi based on spatially-explicit information. This manuscript consists of three steps: i) scenario development, ii) modelling the associated land use and land cover change, and iii) effects of the conservation policy on land conversion (protected areas). One observation of this study is that GDP and population will increase in these three countries, which will influence the demand for food, therefore on agricultural lands. Conservation policy can decrease the forest loss; however a leakage effect can occur, when more forest lands are located outside of protected areas (in Uganda).

The topic is relevant and interesting. However, the whole process of the study was not clearly explained, therefore it is not repeatable from its current form of writing. In addition, throughout the article, arbitrary compromises in analysis are invoked, some of which are unjustified given the current explanation such as price effects, technology changes etc. The manuscript would need to be significantly improved.

Please allow me to suggest following:

* The introduction needs to be considerably improved with respect to the current knowledge on this topic. The main topic of this manuscript is spatial 'trade-off' between agricultural production and biodiversity, in other words, trade-offs that occur due to the conflict of interests on land use. In the current scholarly knowledge, this topic has been addressed in various approaches and the reader will benefit if the manuscript introduces how the main topic has been investigated in other researches and what the added value of this manuscript on this relevant topic would be.

We agree with the reviewer in that the topic has been addressed by other scholars. We have made changes to the introduction to incorporate the current state of knowledge on the topic and the added value of our study.

* In the second paragraph of the introduction, the drivers of changes have been addressed, such as population growth and GDP. However, the connection is rather weak or not explained enough. How would increasing GDP influence the land use, or how will the consumption pattern be expected to be changed in this region? This explanation comes in discussion finally, but if it comes earlier, the readers would benefit from the clear explanation and the scope of the study.

We have moved the explanation of the link between GDP and consumption patterns from the discussion to the introduction and added further references.

* Methods could be improved by providing more information on the characteristics of the study region. The authors explained later in the result and discussion section how changes will influence biodiversity in areas with high biodiversity values such as Albertine rift valley and Victoria Lake. Without pre-knowledge of the current situation and the value of those areas, it is not straightforward for readers. Please add more explanations of the region, and preferably a map of the region.

We have added a section (2.1) on the study region. We have also added a map of the study region to the supplementary material showing the location of the key biodiversity areas.

* In fact, the scenario development is the key to understand the changes. All results were presented according to the four scenarios. However, it is poorly explained, especially with respect to the stakeholder workshop and the process of choosing the key words. This manuscript didn't provide

an answer for those questions: Who were the stakeholders?; What was the procedure to develop the four scenarios?; How were the main terms ('regional integration' and 'mode of governance') chosen among others?; and what were the other options?. It seems that the information has been provided in the other source (e.g. a link to the website), however, it would be beneficial to have a brief background in the text. Furthermore, as abovementioned, 'regional integration' and 'mode of governance' were the main features to create four combinations. If it is the key issue, it would be relevant to introduce earlier, how important the regional integration and governance is in understanding
trade-offs and land use change.

The section on scenarios (2.2) has been extended with more details on the stakeholders involved in the scenario development and the process of selecting the key drivers. Some further references on the scenario development process have also been added. We added a sentence to the introduction on the importance of governance challenges in East Africa.

* Another concern in scenarios is that the differences in land use change and the impact on biodiversity among those four scenarios are not big enough and not clearly visualised on the maps (Fig 5 and 6). Then, the readers might doubt why we need to have the four scenarios. Please provide examples of and justify why those four scenarios and the comparison should be done and needed, and highlight them.

We have improved figures 5 and 6 to address this, using different colour ramps and highlighted areas of change which helps in comparing the four scenarios and identifying difference between them.

* A flowchart of the modelling work would benefit in the method chapter. Two models have been presented in the manuscript; however there have been more sub-models in different aspects of agricultural production, which hinders the ability to follow the detail of the work. Methods could be improved by providing more information on what types of data have been used and how those modelling works were interconnected.

We agree that a flowchart would benefit the methods chapter. However, since each figure counts for 300 words we could not include this without removing any of the other figures or text. A flow chart has been added to the supplementary material.

* Line 10 (page 9) The definition or explanation of terminology (i.e. crop yields and crop production) was not clearly stated earlier, but only came in the beginning of the discussion. Furthermore, crop yields and crop production is confusing as both can indicate the supply side of food, not the demand directly. I would suggest changing the terms. In addition, in Fig 4 the overall pattern between crop yield and production seems similar except for rice (low in yield, but high in production in Rwanda and Burundi). Please explain it.

We have moved the explanation of the terms crop yields and crop production to the earliest mention in the manuscript. We do not see any reason to change the terms. Both crop yield and crop production are widely used in literature on this topic. In addition, we cannot change the terms without considerable changes to the manuscript, including figures. The low yield increase for rice and greater increase in production in figure 2 is due to the low production of rice in Rwanda and Burundi. Therefore, small changes in production appear as relatively large deviations. Rice yields in both countries are not very high, so if there is a push for more production, than some of this will have to come from increased area dedicated to rice.

* This manuscript is based on a practical approach using scenario developments with stakeholders. However, the authors' recommendation and the lessons learnt from the scenario development are missing. Please provide them in the conclusion chapter.

The key focus of this manuscript is about the use of socio-economic scenarios in land use modelling and analysis of potential impacts on biodiversity and spatial trade-offs between food production and biodiversity and to a lesser extent about the actual scenario development with stakeholders. Lessons learnt from the scenario development for this region are well described in Vervoort et al, 2014 and Chaudhury et al., 2013.

Some specific minor comments are following:

* Line 27 (page 2) 'mitigate global warming' seems irrelevant. The authors claimed that the demand on bioenergy (the production of agricultural commodities) increases in order to reduce carbon emission in line 12 (page 2). The sentence in line 27 is then contradicting. Overall, as the authors don't discuss further the demand for bioenergy through the manuscript, focusing on food production would be clearer. Indeed, trade-offs can occur between different uses of agricultural areas such as food vs. bioenergy. An introduction of bioenergy at the very beginning of the introduction chapter could give an impression that the manuscript deals with trade-offs among food production vs. bioenergy vs. biodiversity of the region. If bioenergy crop is not a particular interest of the manuscript, please reconsider it.

We agree with the reviewer and have removed the wording around bioenergy and mitigation of global warming.

* Line 10 (page 3), numbering is wrong. 2. Methods (instead of 3. Methods) and please check again through the whole manuscript.

Changed and checked through the manuscript.

* Line 53 (page 7) 'more area'. Please provide the number (ratio or differences) to support the statement.

Ratio now included

* Line 14-16 (page 10) and Line 38 (page 12) regarding the price effect, please justify it.

We have added more text on the price effect in section 4.1 (results)

"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"

* Fig 5. The difference among four scenarios is not clearly feasible. Could you probably highlight them? Or present the differences? Did you include the protected areas in this analysis as well in Fig 5? Could you present where the protected areas were and how they were changed?

The figure now includes the location of protected areas in the region. We have added circles to the map to highlight key areas of change and differences between the scenarios.

* Fig.6. please provide the legend clearly. Two different colour scales (i.e. green and brown) were presented, but the meaning of them were not clearly stated. It is only assumed that 'High' in the green bar is the high biodiversity value, whereas 'high' in the brown bar represents the high loss of biodiversity. The difference among four scenarios is not feasible.

We have altered the legend to address this. We have also added circles to this figure to highlight key areas of change and differences between the scenarios.

References:

Chaudhury, M., Vervoort, J., Kristjanson, P., Ericksen, P., & Ainslie, A. (2013). Participatory scenarios as a tool to link science and policy on food security under climate change in East Africa. *Regional Environmental Change*, *13*(2), 389-398.

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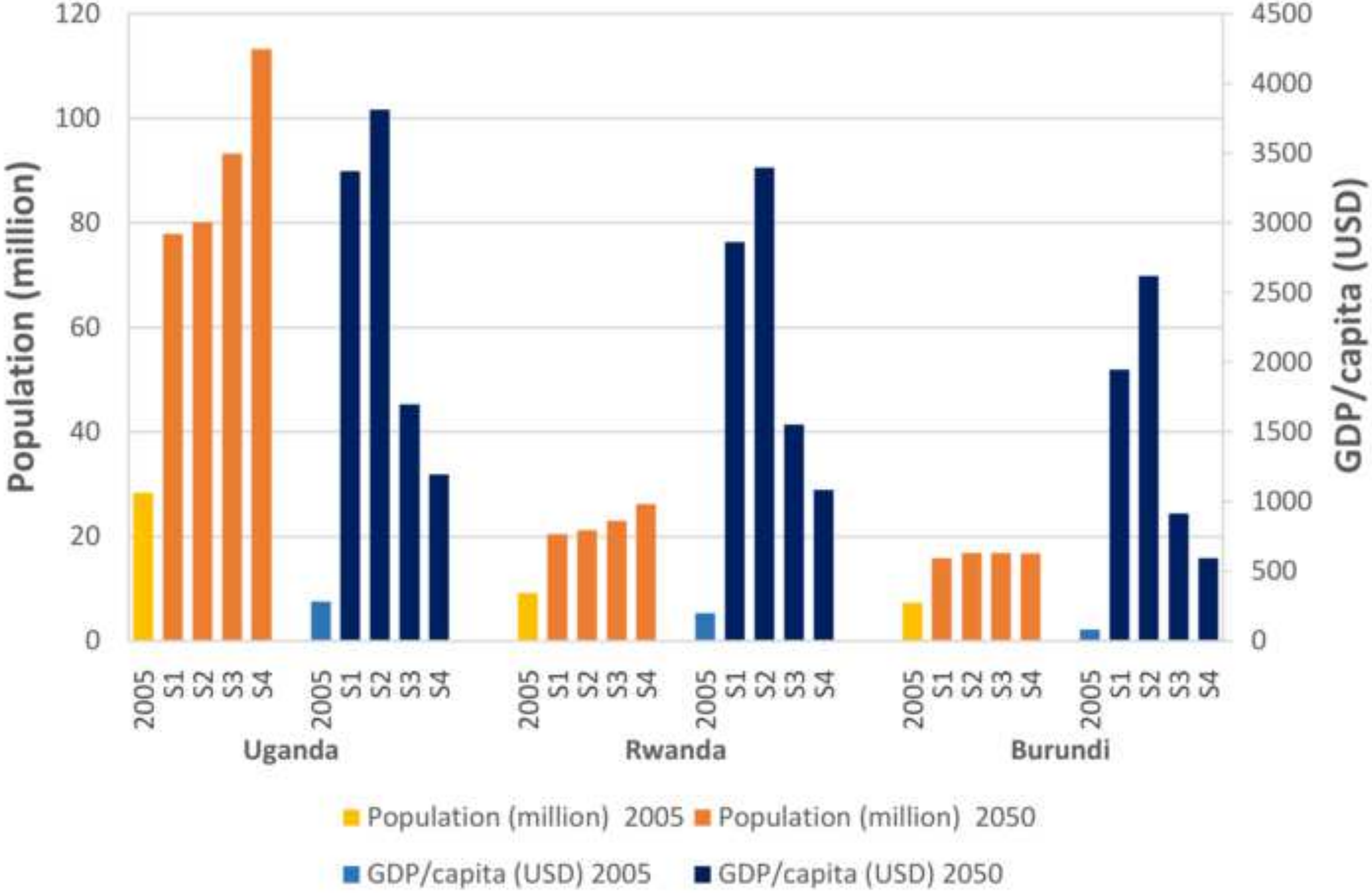
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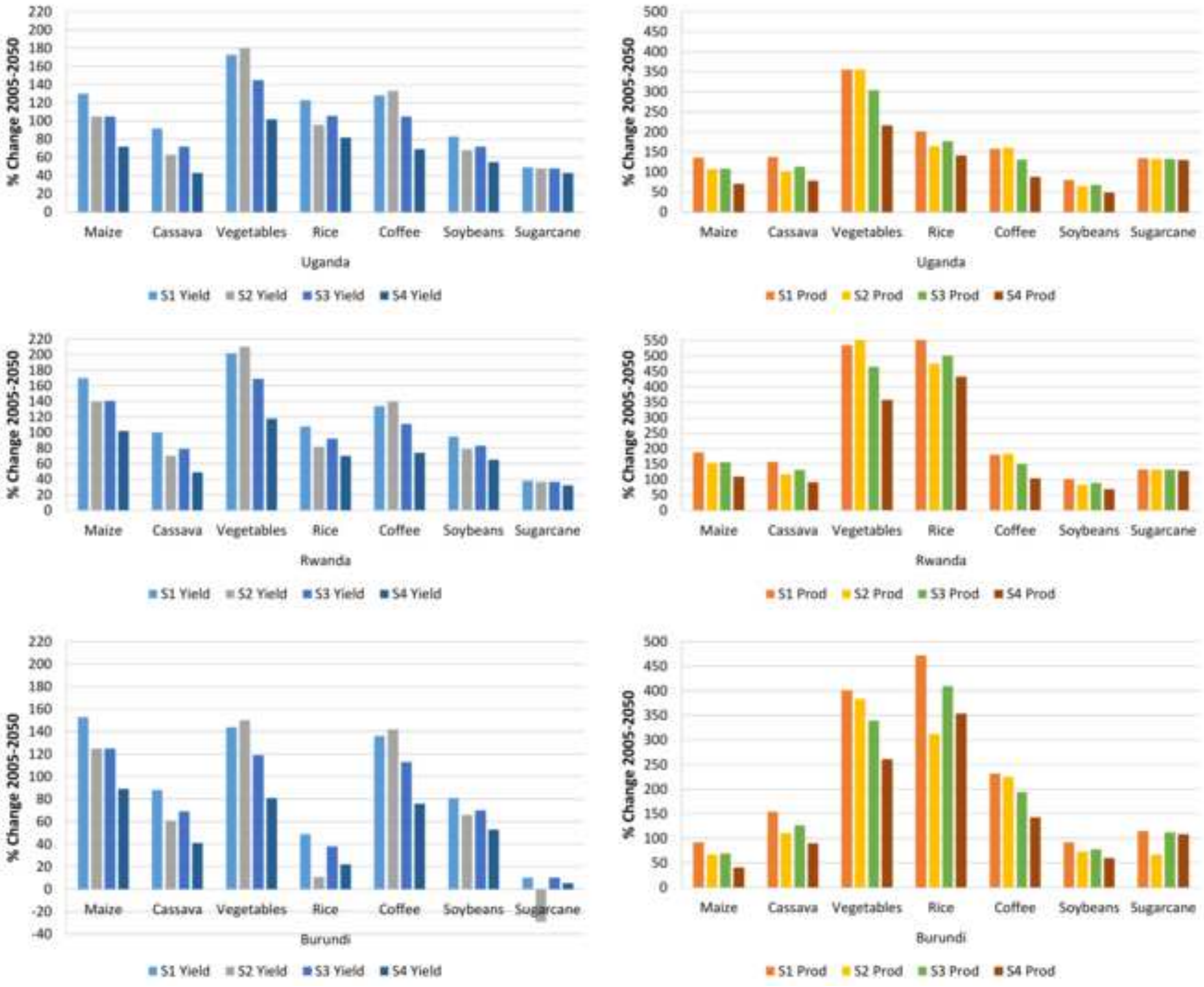
Population (million) 2050
GDP/capita (USD) 2005
GDP/capita (USD) 2050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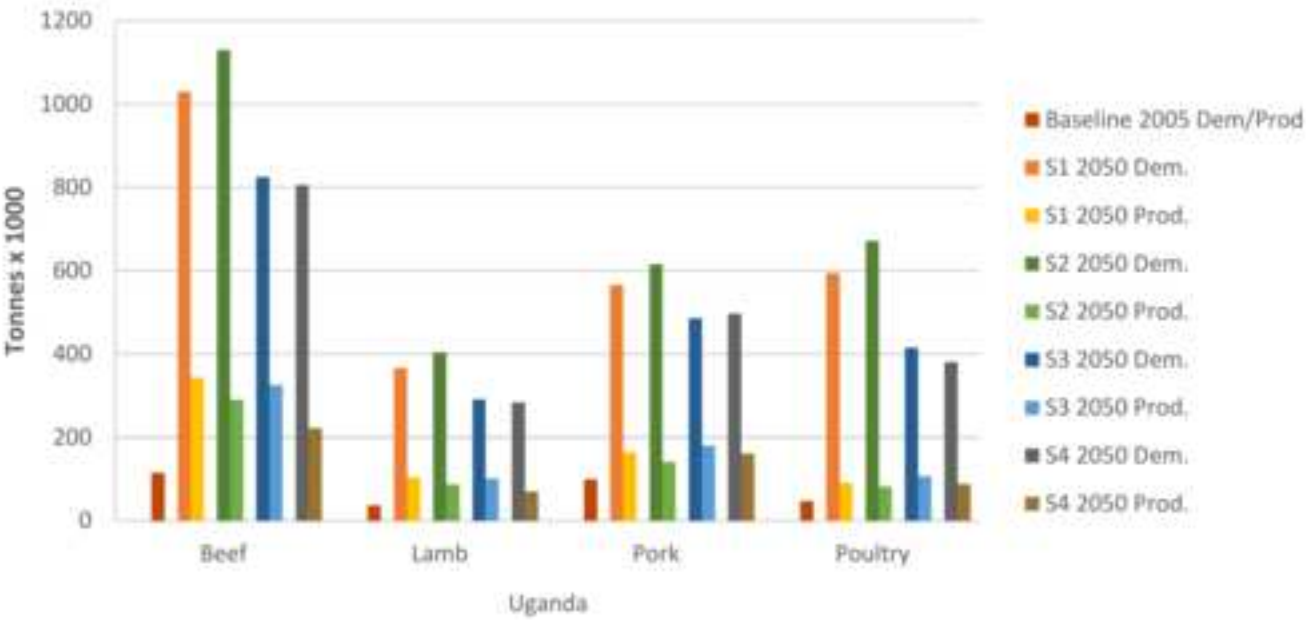
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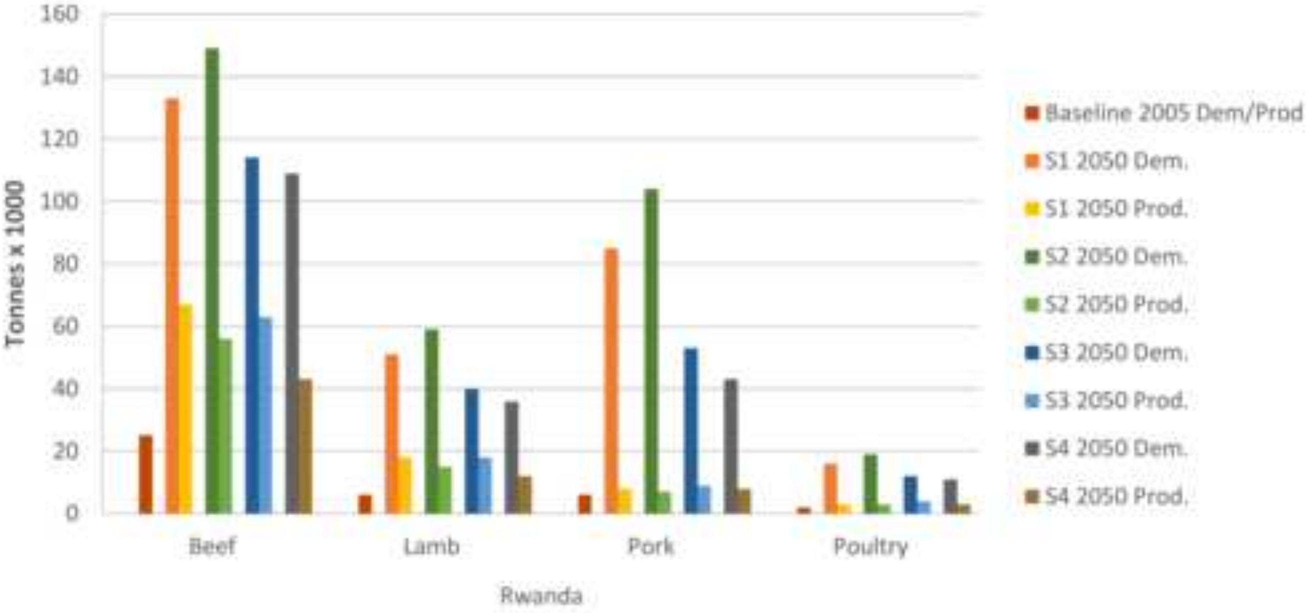
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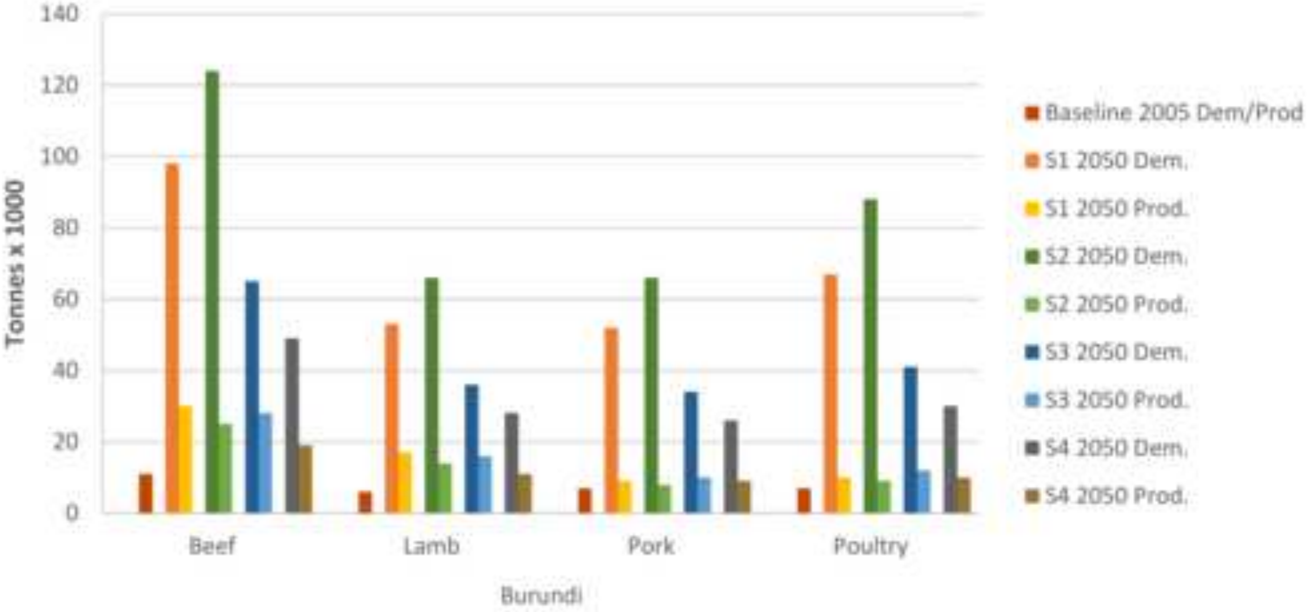
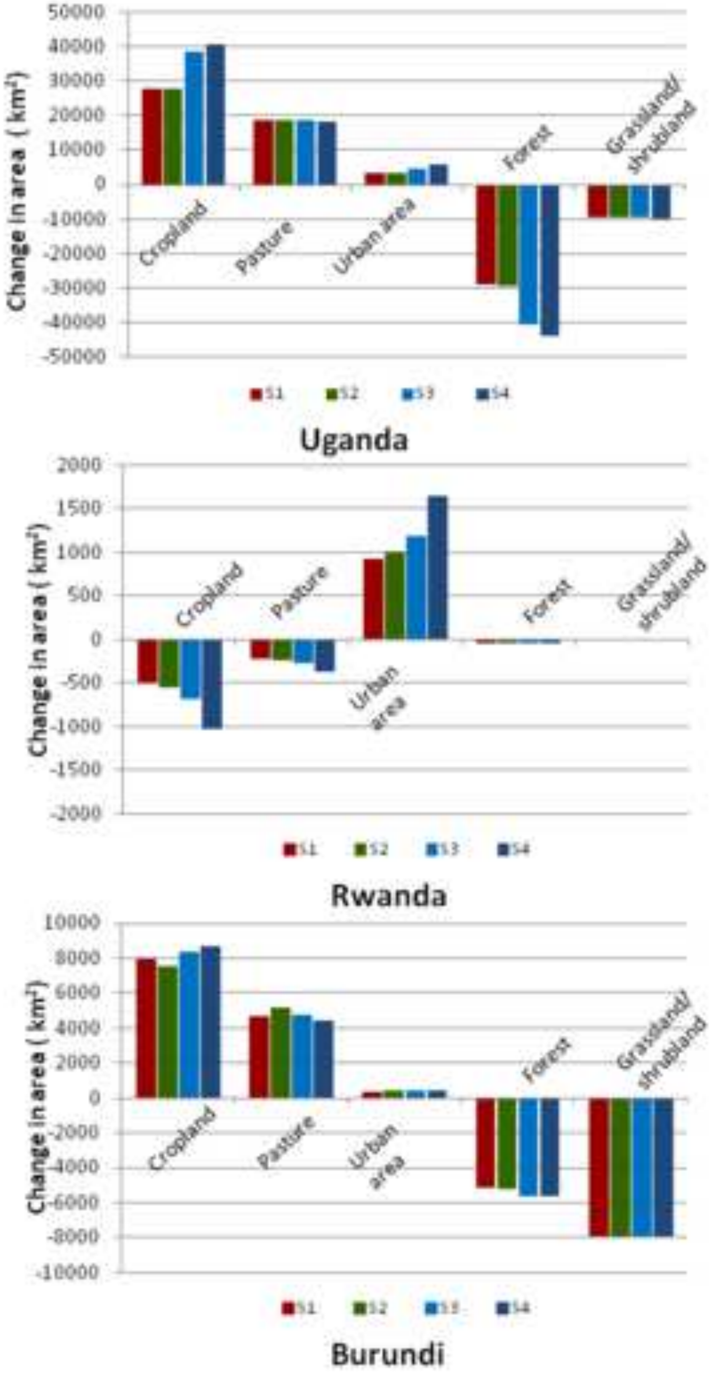
Baseline 2005 Dem/Prod
S1 2050 Dem.
S1 2050 Prod.
S2 2050 Dem.
S2 2050 Prod.
S3 2050 Dem.
S3 2050 Prod.
S4 2050 Dem.
S4 2050 Prod.


140
120
100
80
60
40
20
0
Tonnes x 1000
Beef
Lamb
Pork
Poultry
Burundi
Baseline 2005 Dem/Prod
S1 2050 Dem.
S1 2050 Prod.
S2 2050 Dem.
S2 2050 Prod.
S3 2050 Dem.
S3 2050 Prod.
S4 2050 Dem.
S4 2050 Prod.

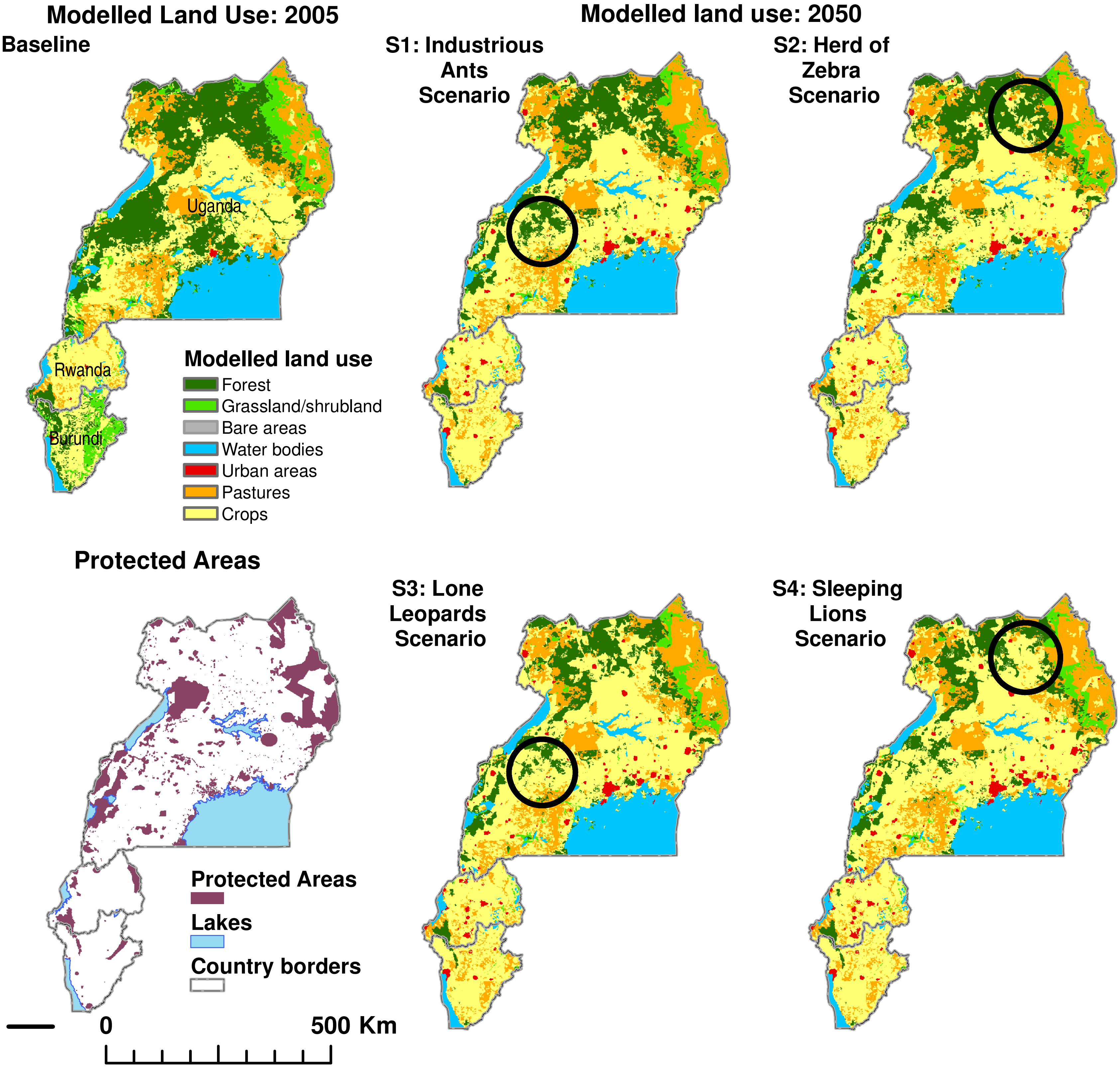


Uganda

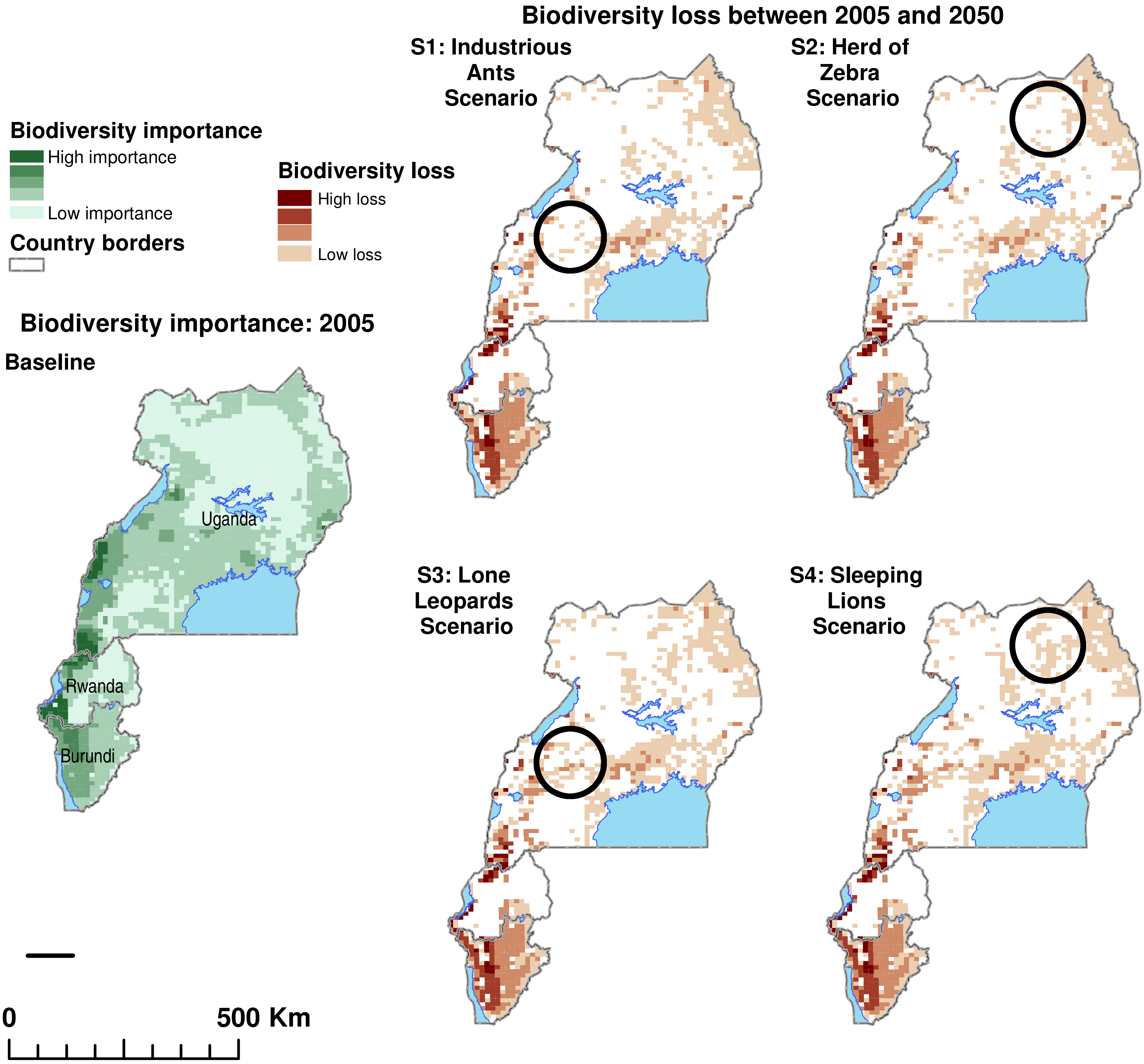
Rwanda

Burundi

Figure


Modelled Land Use: 2005
Baseline
Uganda
Rwanda
Burundi
Modelled land use
Forest
Grassland/shrubland
Bare areas
Water bodies
Urban areas
Pastures
Crops
Modelled land use: 2050
S1: Industrious Ants Scenario
S2: Herd of Zebra Scenario
Protected Areas
Protected Areas
Lakes
Country borders
0
500 Km
S3: Lone Leopards Scenario
S4: Sleeping Lions Scenario

Figure


Biodiversity loss between 2005 and 2050
S1: Industrious Ants Scenario
S2: Herd of Zebra Scenario
S3: Lone Leopards Scenario
S4: Sleeping Lions Scenario
Biodiversity importance
High importance
Low importance
Country borders
Biodiversity loss
High loss
Low loss
Biodiversity importance: 2005
Baseline
Uganda
Rwanda
Burundi
0
500 Km

Supplementary material

Impacts of future agricultural development on biodiversity at regional scales: a spatially explicit assessment of trade-offs in Uganda, Rwanda and Burundi.

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1. Methods

1.1 Study Area

Figure S1 shows the study area with the location of key biodiversity areas in the region.

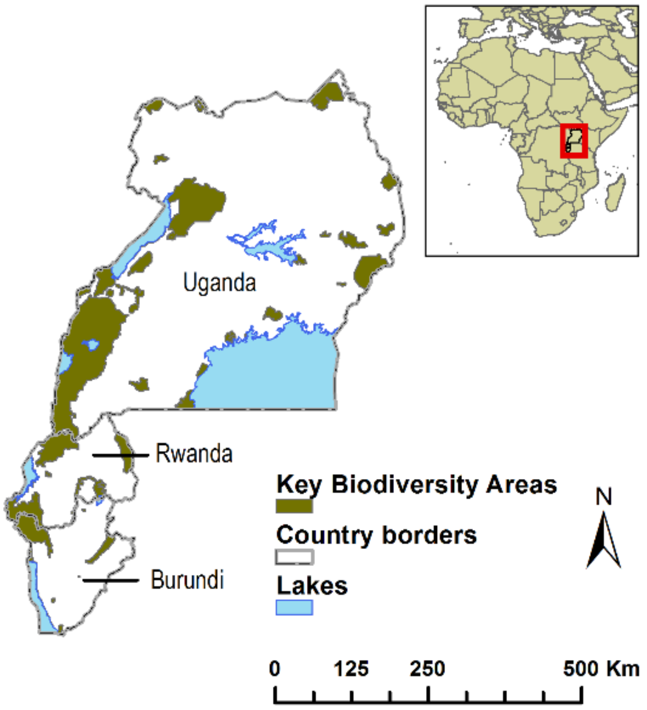

Figure S1: Study area with location of Key Biodiversity Areas. Data: Birdlife International (2013) World Bird and Biodiversity Areas Database. Available at: www.birdlife.org

1.2. Modelling framework

A flowchart of the modelling framework is presented in figure S1 with the main analysis framework in blue, supporting models and input data in green and the regionally developed scenarios in orange. The scenario narrative and semi-quantification were used in the IMPACT and LandSHIFT modelling.

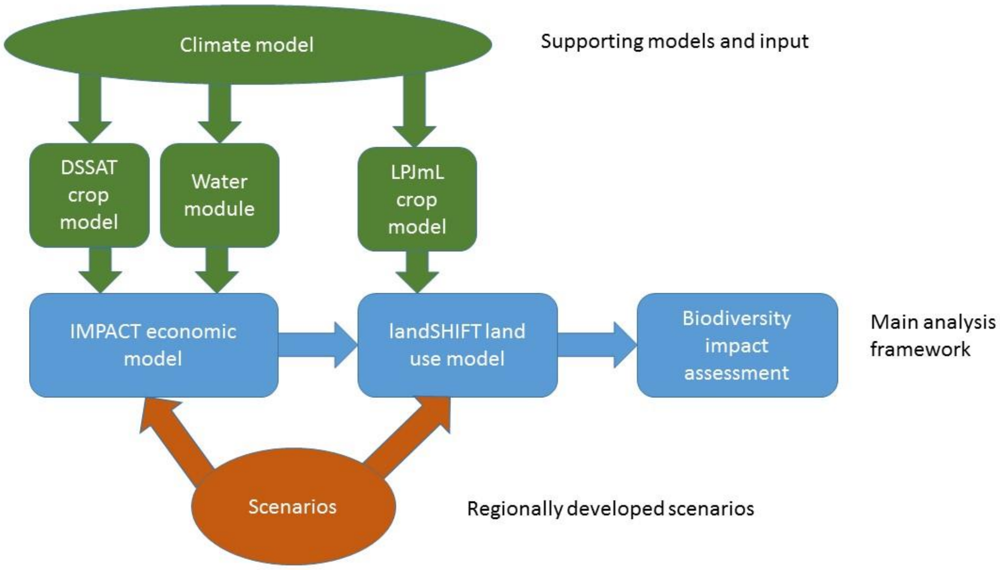

Figure S1: Modelling flowchart. In green, supporting models and input data. Orange the regionally developed scenarios. Blue, the main analysis framework

1.3 Scenario narrative summaries

S1: Industrious ants - strong regional integration and proactive governance. This scenario features slow but strong economic and political development in East Africa, accompanied by proactive government action to improve regional food security. However, on the down side, costly battles with corruption continue and peace is fragile, since the region has to deal with new international tensions as a result of its growing prominence on the global stage. The region's focus on the production of staple foods, rather than high-value crops for export, undermines its participation in the global market for a time, while an over-reliance on trade within the region causes problems when severe drought hits in 2020. By that time, though, many government and non-government support structures are in place to mitigate the worst impacts. Governments and their partners work well together and achieve some success in mitigating the adverse environmental impacts of increased food and energy production, although the need to put food security and livelihoods first overshadows these efforts from time to time.

S2: Herd of Zebra - strong regional integration but reactive governance. In this scenario, governments and the private sector push strongly for regional development, but mainly through industry, services, tourism and export agriculture, with limited action on food security, environments and livelihoods. East African economies boom, but the region suffers the consequences of its vulnerability to global market forces and unsustainable environmental exploitation. Only when food insecurity becomes extreme, following rocketing food prices during the Great Drought of the early

2020s, is action taken to improve the management of water resources and invest in climate-smart food production for regional consumption.

S3: Lone Leopards - continued fragmentation but proactive governance. In this scenario, regional integration exists only on paper by 2030. In reality, government and non-government institutions and individuals are busy securing their own interests. In terms of food security, environments and livelihoods, the region initially seems to be heading for catastrophe in the 2010s. However, after some years, national and international as well as government and non-government partnerships become more active and, unburdened by strict regional regulations and supported by international relations, are able to achieve some good successes by the 2020s. Unfortunately, because of the lack of coordination, this is a hit and miss affair, with some key issues ignored while on others there are overlapping or competing initiatives. The inability of governments to overcome regional disputes and work with one another becomes untenable when a severe drought hits in 2020. This pushes civil society, bolstered by international support, into a demand for radical change in governance. In many cases, the resulting change is long lasting and for the better.

S4: Sleeping Lions - regional fragmentation and reactive governance. This scenario is all about wasted potential and win–lose games. Governments in 2030 act only in response to serious situations and in ways to further their own self-interests, thereby allowing foreign interests free rein in the region. Their actions – or lack of them – have devastating consequences for East Africans’ food security, livelihoods and environments. Conflicts, protests and uprisings are common, but each time reform is promised, it fails to materialize. The lack of coordinated effort on climate change and its impacts means that a severe drought occurring in 2020–2022 results in widespread hunger and 100 many deaths among the region’s poor and vulnerable. It is only the adaptive capacity and resilience of communities, born out of decades of enforced self-reliance based on informal economies, collaboration and knowledge sharing that mitigates the worst effects of this disaster. The first signs of better governance emerge only in the late 2020s, but the region’s population still faces a very uncertain future.

Table S1 East African scenarios, drivers and driver states based on Vervoort et al. (2013)

Scenarios	**Regional integration**	**Governance**
S1: Industrious Ants	Integrated	Proactive
S2: Herd of Zebra	Integrated	Reactive
S3: Lone Leopards	Fragmented	Proactive
S4: Sleeping Lions	Fragmented	Reactive

1.4 Landshift model

LandSHIFT simulates LUCC in five year time steps from 2005 to 2050 at a spatial grid cell resolution of ~0.85 km^2.The model uses a multi criteria analysis which is carried out at the grid cell level for the crop, urban and livestock sub-models. Cells are ranked regarding their potential suitability for each of the sub-model`s sectors. Highest ranked cells are primarily utilized for crop production. The multi criteria analysis for crop allocation considers five weighted criteria (table S2): proximity to existing cropland, population density, terrain slope, distance to next road, and crop yields based on the LPJmL model. The criteria weights are analyzed from the occurrence of cropland cells for the year 2005 using

ESA GLOBCOVER land-cover data based on satellite images (ESA 2014; Bicheron et al. 2008). The relative importance of each criterion is calculated by comparing the difference between the average criteria value of true cells where cropland occurred and false cells where no cropland occurred on the country level (compare with Lapola et al. 2011). The obtained differences are normalized to fit in the multi criteria calculation

Finally, the weights describe the importance of each criterion for the occurrence of cropland with the assumption that the analyzed criteria weights are also suitable to explain future cropland distribution, which is truly uncertain. During the baseline initialization, cropland is primarily distributed to GLC2000 LUT "cultivated and managed land" (LUT 16) and secondary to the rather extensively utilized "mosaic cropland: tree cover /other natural vegetation" (LUT 17) and "mosaic: cropland / shrub or graze cover"(LUT 18). Cropland distribution into PA and KBA areas is only allowed for cells of LUT 16 as these cells are already intensively used for crop cultivation, in terms of cropland extend. For the scenarios computation, unutilized LUT 17 and LUT 18 are treated as natural woodland and shrub-land habitats. Future crop allocation is spatially distributed according to the multi criteria analysis in LandSHIFT.

Table S2 Country specific weight parameters used in LandSHIFT model

Weight parameters - Country specific					
country	crop yields LPJml	Proximity	population density	slope	infrastructure road
Rwanda	0.118809	0.617846	0.0484493	0.0339302	0.180966
Burundi	0.46949	0.13564	0.08996	0.27997	0.02493
Uganda	0.258443	0.0485998	0.554268	0.107744	0.0309458

1.5 Climate change projections

Table S3 shows the projections for temperature and precipitation as a mean change for the region under the RCP 8.5 scenario for 2050 using the IPSL-CM5A-LR—The Institut Pierre Simon Laplace's Earth System Model climate model.

Table S3 projections for temperature and precipitation for East Africa region under RCP8.5 scenario for 2050 using the IPSL GCM.

	Change 2005-2050
Precipitation	+ 53 mm / year
Temperature	+ 2.95° C

1.6 Biodiversity assessment

The metric of relative biodiversity uses suitable habitat for species in the region. The suitable habitat for individual species is based on a crosswalk table between LandSHIFT land use types and IUCN habitat classes, which are based on expert opinion and literature (IUCN, 2013). This crosswalk table is based on a study by Foden et al. (2013) and was originally created to allow the refinement of IUCN species' EOOs by linking IUCN habitat classes to the Land Cover Classification System (LCCS), the classification system used by GLC2000. Although GLC2000 was used as a basis for land use modelling, the LandSHIFT model provides additional classes for crop, pasture and set-aside areas, thus a number of additional links were added to these classes. We only included EOOs listed as extant; native or reintroduced and with seasonal attributes listed as either resident, resident breeding or resident non-breeding. We only included habitat categories classed as suitable, thus excluding marginal habitats.

For each ~10x10 km grid cell, biodiversity values are assessed as follows:

For the baseline situation:

Equation 1: $\text{Biodiversity}_{gs} = \sum_1^i \left(\left(\frac{H\,gi_{t_0}}{\sum_1^G Hgi_{t_0}} \right) \cdot \left(\frac{R_i}{EOO_i} \right) \right)$

With H: area of grid cell where a species (i) is counted as present in a grid cell (g) in the baseline situation (t0), EOO_i: The species total extent of occurrence, R_i: Overlap of the EOO with the region

To assess change in this metric between the future and baseline situation, the relative loss was assessed relative to the baseline situation (Equation 2).

Equation 2: $\text{Biodiversity loss}_{gs} = \sum_1^i \left(\left(\frac{H\,gi_{t_1} - H\,gi_{t_0}}{\sum_1^G Hgi_{t_0}} \right) \cdot \left(\frac{R_i}{EOO_i} \right) \right)$

Where t1 is the future or scenario period and $H_i t_1 < H_i t_0$.

2. Additional results

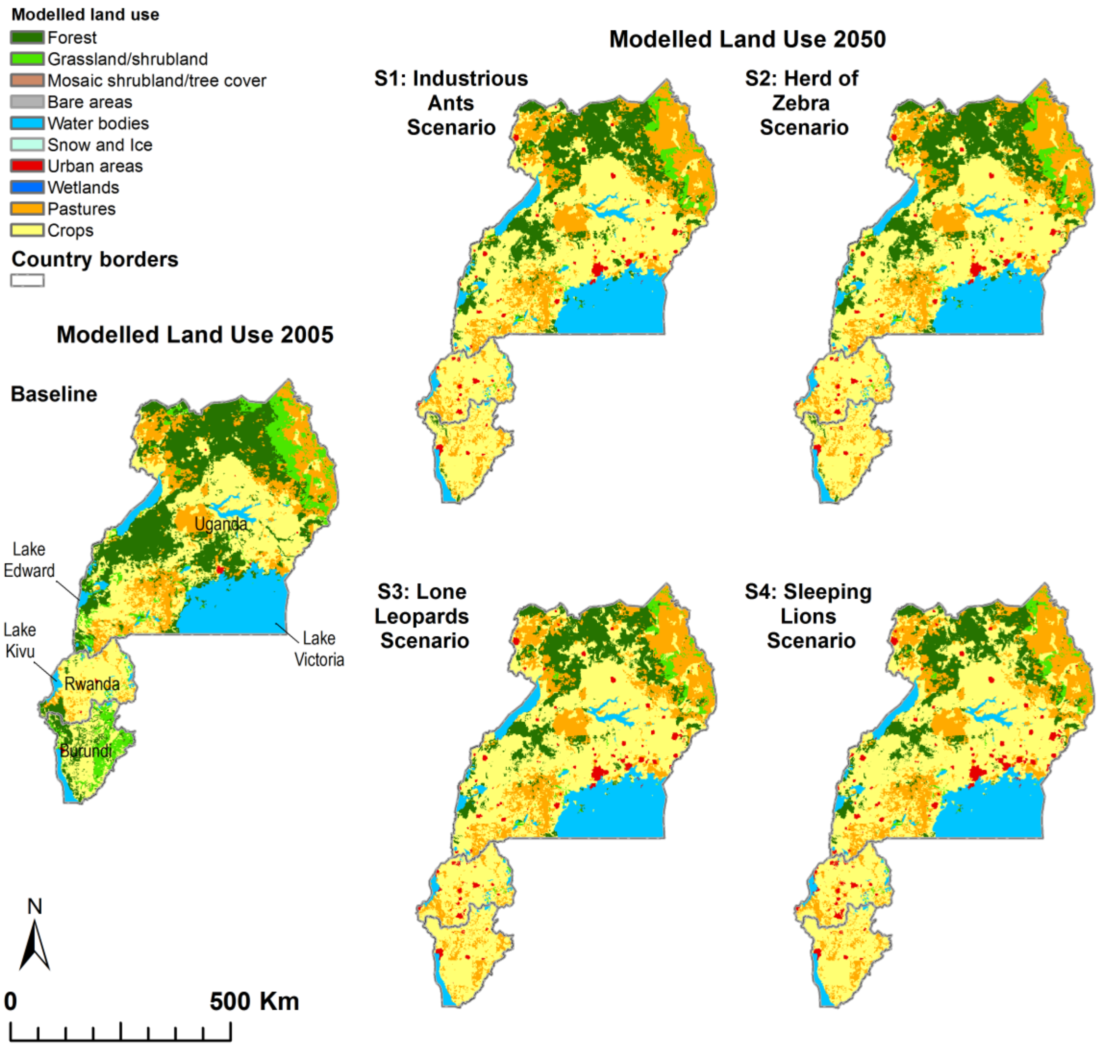

Figure S2 Modelled land use in 2005 and projections for 2050 for four socio-economic scenarios for Uganda, Rwanda and Burundi. Protected areas allowed to convert (PA off)

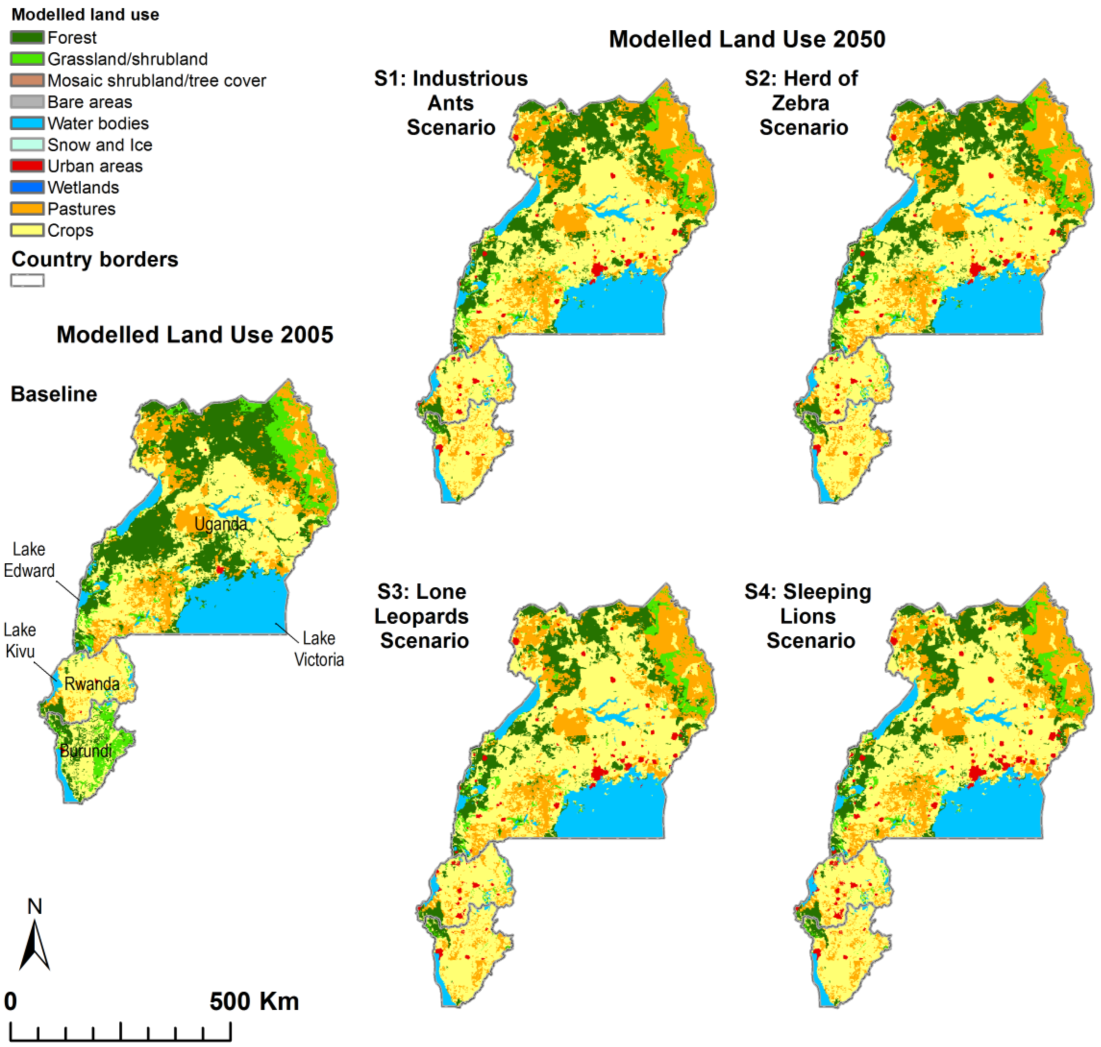

Figure S3 Modelled land use in 2005 and projections for 2050 for four socio-economic scenarios for Uganda, Rwanda and Burundi. Protected areas and Key Biodiversity Areas assumed to remain unconverted (PA+KBA)

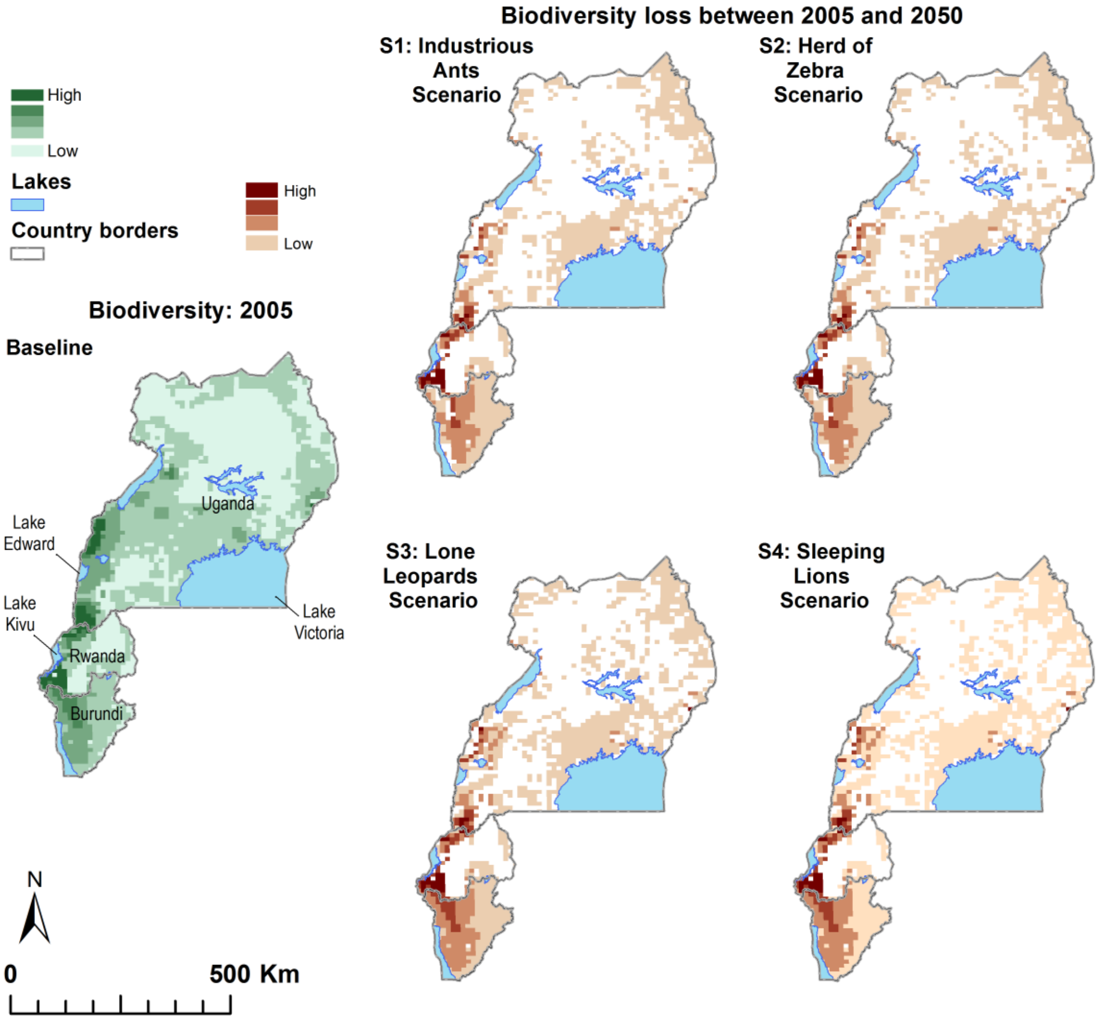

Figure S4 Current biodiversity and projected changes in biodiversity between 2005 and 2050 for four socio-economic scenarios of change for Uganda, Rwanda and Burundi. Protected areas allowed to convert (PA off)

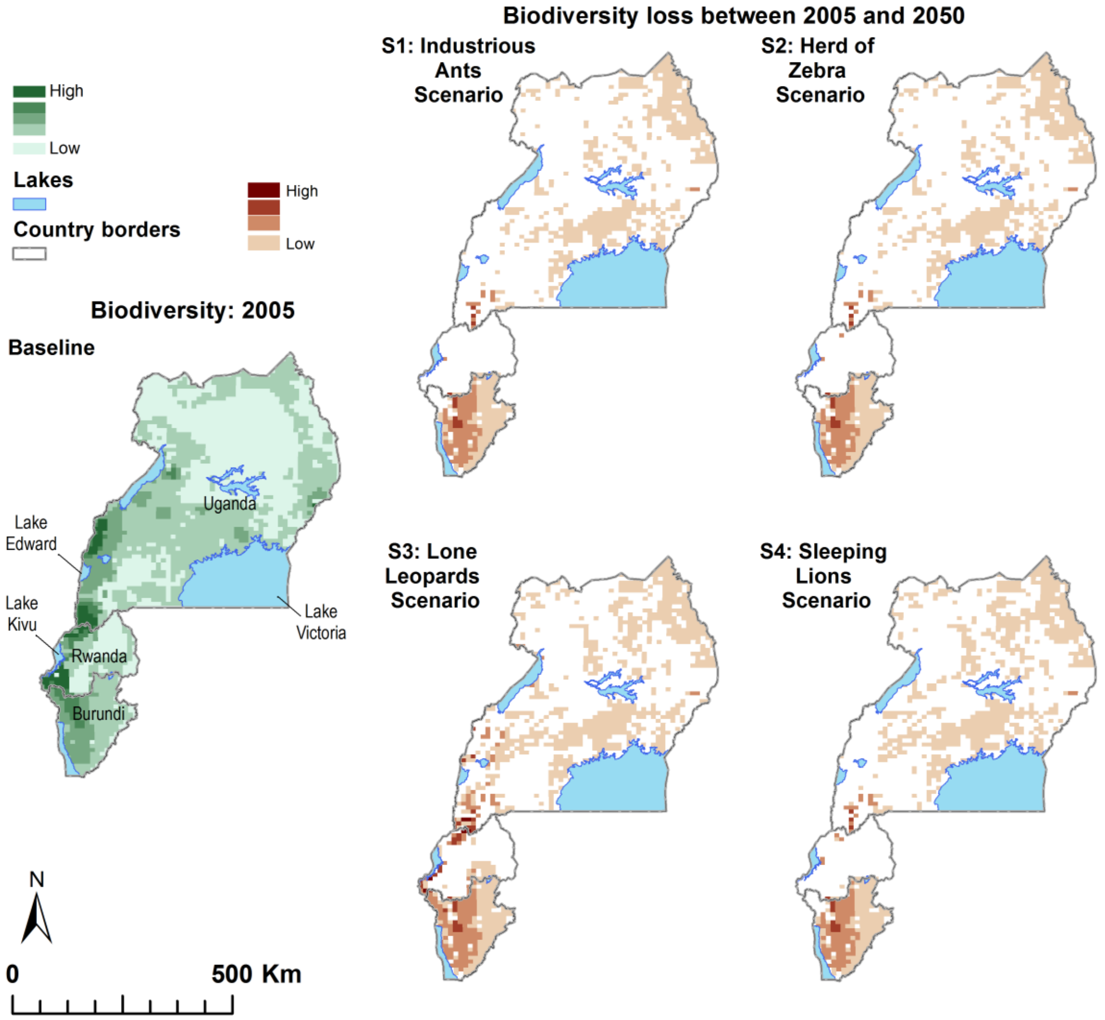

Figure S5 Current biodiversity and projected changes in biodiversity between 2005 and 2050 for four socio-economic scenarios of change for Uganda, Rwanda and Burundi. Protected areas and Key Biodiversity Areas assumed to remain unconverted (PA+KBA)

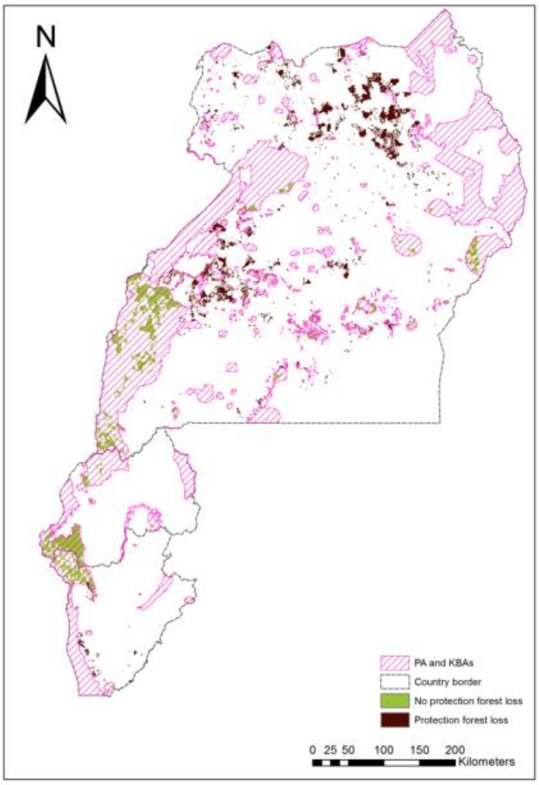

Figure S5 Difference between projected forest loss under a no protection (PA off) and maximum protection (PA+KBA) scenario for the S1 socio economic scenario for Uganda, Rwanda and Burundi.

Table S4 Area of forest in 2050 under four socio-economic scenarios and different conservation policies in Uganda, Rwanda and Burundi. Areas in grey have lost more than 50% of forest cover with respect to the baseline simulation of 2005.

Area of forest in country (km2)																								
	Uganda								Rwanda								Burundi							
	S1 area	S1 %	S2 area	S2 %	S3 area	S3 %	S4 area	S4 %	S1 area	S1 %	S2 area	S2 %	S3 area	S3 %	S4	S4 %	S1 area	S1 %	S2 area	S2 %	S3 area	S3 %	S4 area	S4 %
2005_KBA+PA_on	83,338		83,338		83,338		83,338		2,088		2,088		2,088		2,088		6,240		6,240		6,240		6,240	
2050_PA_off	56,027	-32.8	55,801	-33.0	45,816	-45.0	42,210	-49.4	8	-99.6	7	-99.7	1	-100.0	1	-100.0	851	-86.4	806	-87.1	0	-100.0	0	-100.0
2050_PA_on	55,736	-33.1	55,462	-33.4	17,442	-79.1	17,430	-79.1	1,368	-34.5	1,368	-34.5	1,354	-35.2	1,351	-35.3	1,000	-84.0	971	-84.4	625	-90.0	626	-90.0
2050_PA+KBA_on	54,405	-34.7	54,133	-35.0	43,234	-48.1	40,114	-51.9	1,995	-4.5	1,991	-4.6	1,979	-5.2	1,960	-6.1	1,725	-72.4	1,723	-72.4	1,723	-72.4	1,724	-72.4
Area of forest in Pas (km2)																								
2005_KBA+PA_on	17,486		17,486		17,486		17,486		1,355		1,355		1,355		1,355		626		626		626		626	
2050_PA_off	13,517	-22.7	13,477	-22.9	11,897	-32.0	11,478	-34.4	3	-99.8	2	-99.9	1	-99.9	1	-99.9	238	-62.0	225	-64.1	0	-100.0	0	-100.0
2050_PA_on	17,450	-0.2	17,450	-0.2	17,442	-0.3	17,430	-0.3	1,355	0.0	1,355	0.0	1,354	-0.1	1,351	-0.3	626	0.0	625	-0.2	612	-2.2	613	-2.1
2050_PA+KBA_on	17,450	-0.2	17,450	-0.2	17,442	-0.3	17,430	-0.3	1,355	0.0	1,355	0.0	1,354	-0.1	1,351	-0.3	626	0.0	625	-0.2	625	-0.2	626	0.0
Area of forest in Pas and KBAs (km2)																								
2005_KBA+PA_on	21,350		21,350		21,350		21,350		2,043		2,043		2,043		2,043		1,781		1,781		1,781		1,781	
2050_PA_off	14,369	-32.7	14,335	-32.9	12,429	-41.8	11,988	-43.9	8	-99.6	7	-99.7	4	-99.8	4	-99.8	540	-69.7	511	-71.3	0	-100.0	0	-100.0
2050_PA_on	17,488	-18.1	17,487	-18.1	17,033	-20.2	16,952	-20.6	1,362	-33.3	1,362	-33.3	1,361	-33.4	1,358	-33.5	755	-57.6	736	-58.7	582	-67.3	583	-67.3

2050_PA+KBA_on	20,337	-4.7	20,327	-4.8	20,078	-6.0	19,934	-6.6	1,951	-4.5	1,947	-4.7	1,935	-5.3	1,916	-6.2	1,690	-5.1	1,688	-5.2	1,688	-5.2	1,689	-5.2

Table S5 relative change in biodiversity loss for no protection (PA off) and extended protection (PA+KBA) from a effective protection (PA on) baseline (percentage)

	Uganda		Rwanda		Burundi	
	PA off	PA+KBA	PA off	PA+KBA	PA off	PA+KBA
S1	46.8	-38.4	152.2	-91.0	4.1	0.1
S2	46.1	-38.8	152.2	-92.6	4.9	1.1
S3	62.6	-36.9	163.2	-90.9	35.0	-13.1
S4	58.5	-34.9	160.7	-87.4	35.0	-13.1

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