The distribution of threats from future agricultural development for biodiversity and ecosystem services in the Lake Victoria Basin

Implications for policy

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The distribution of threats from future agricultural development to biodiversity and ecosystem services in the Lake Victoria Basin: Implications for policy

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Glossary

CCAFS: Climate Change Agriculture and Food Security research program of the Consultative Group on International Agricultural Research (CGIAR)
FAO: Food and Agriculture Organisation of the United Nations
GCM: Global Circulation Model
GDP: Gross Domestic Product
GEO: Global Environment Outlook
IFPRI: International Food and Policy Research Institute
IMPACT: International Model for Policy Analysis of Agricultural Commodities and Trade
IPCC: Intergovernmental Panel on Climate Change
IPSL: Institut Pierre Simon Laplace - climate model
LCCS: Land Cover Classification System of the Food and Agriculture Organisation of the United Nations
RCP: Representative Concentration Pathway
UNEP-WCMC: UN Environment World Conservation Monitoring Centre

Executive Summary

Over the coming decades, society will have to balance competing needs for land to feed the growing human population, provide resources and energy to satisfy the ever-accelerating human consumption, slow global warming and reduce the rate of loss of ecosystem services and biodiversity. Decision makers need to balance different demands on land and take into account potential changes in these demands in the future, for example due to projected population growth, urbanisation and climate change. At the same time many other and more uncertain factors may influence that future, such as globalisation and trade agreements, commodity markets, governance regimes and regional integration, and therefore affect policy outcomes.

Implications for biodiversity and ecosystem services of demands upon land may vary through time and space. It is therefore crucial that decision makers have access to spatially explicit information and analyses on the potential effects of different trajectories of human-induced landscape change. This information can support the development of policies that are robust and adaptable so that they achieve their intended outcomes even under an unpredictable future.

This technical report is an output of UNEP-WCMC's project on *Engaging stakeholders in using scenarios of land use change due to agricultural commodity development in the Lake Victoria Basin* funded by the John D. and Catherine T. MacArthur Foundation. The report presents results of spatial analyses in support of the project objective to "provide analyses and baseline data to support decision-making in relation to the potential future impacts of major commodity developments on biodiversity in short-term and long-term planning in the Lake Victoria Basin".

This report aims to be a two-fold source of information for national and regional stakeholders who influence agricultural and conservation policy and planning in the Lake Victoria Basin. Such stakeholders may include governments, the relevant regional authorities, as well as civil society or researchers. It presents and applies an analytical framework to assess and visualise likely future impacts on biodiversity and ecosystem functions under different socio-economic futures for East Africa and discusses implications for policy. The document does not aim to provide specific policy recommendations for agricultural development in the Lake Victoria Basin. Rather, it aims to provide plausible future contexts within which policy balancing agriculture development and conservation needs to operate. A companion document sets out guidance on how spatially explicit scenario analysis can be used to support development of sustainable agricultural policy.

Analytical framework

Using an analysis framework that considers spatially explicit drivers of land-use change, including changes in human population, commodity markets and agricultural production, potential impacts on biodiversity and ecosystem services were assessed for all watersheds of the Lake Victoria Basin. The Lake Victoria Basin boundary covers parts of five countries: Kenya, Tanzania, Uganda, Rwanda and Burundi. The analysis framework uses regionally-developed socio-economic scenarios of change up to 2050 framed by two main drivers of change: governance (reactive or proactive) and level of regional integration. The scenarios were quantified with the IMPACT agricultural economic model producing national projections of agricultural demand and production. These drivers were then applied within the LandSHIFT high-resolution land-use model to project plausible futures of potential landscape change due to likely changes in these drivers. Models were run with projections of climate change based on the Representative Concentration Pathways (RCP) 8.5 emission pathway. In addition, scenarios were analysed using different conservation policy options: a) a strict conservation policy, where no land within existing protected areas was converted to other land uses, b) a no-conservation policy, where land within protected areas was allowed to be converted and c) an extended conservation policy, whereby in addition to existing protected areas, all known Key Biodiversity Areas in the region were assumed to be protected as well.

The potential impacts of land-use change and variability of these impacts within regions were assessed at the watershed scale for biodiversity and ecosystem services. Biodiversity was assessed using a novel index of biodiversity importance based on the relative distribution of suitable habitat for a species in a watershed and in a region. The metric combines known species distribution data for birds, mammals and amphibians from the International Union for Conservation of Nature (IUCN) Red List and an established method of linking species' habitat preferences to land-use/cover types. The assessment of ecosystem services was based on the potential capacity of a land use type to provide goods and services, also called ecosystem functions. The metric is based on binary links between specific land uses and other environmental properties and the ecosystem functions these properties can provide. Potential changes were analysed for commodity provisioning, wild provisioning and regulating ecosystem functions. A separate composite index for current pressure and potential future threat from human activity was also calculated, which included factors other than agricultural change, such as planned infrastructure, presence of natural resources and accessibility.

A freely available web-based tool (http://macarthur.unep-wcmc.org) was developed that can be used to explore all the results for the different scenarios and analyses within each study region (see Appendix V for more detail).

Results

Crop production in the Lake Victoria Basin is projected to increase consistently across all scenarios in the period up to 2050 with production of some crops more than doubling for most countries. However, different scenarios project different amounts of crop production in future, mostly related to large differences in expected crop yields between scenarios. Climate change under the RCP 8.5 scenario has a positive impact on yields for most crops either through direct climate effects on crops or through changes in global prices and subsequent increased investment in yield gains in the region. Changes in land use and spatial patterns of impacts on biodiversity and ecosystem function provision are relatively similar between scenarios. This is because the major underlying drivers of agricultural expansion, population and climate change, have a strong overriding effect under any type of governance or level of regional integration that may characterise the individual scenarios.

A key change, underpinning much of the projected land-use change in this region is the large increase in meat production expected under all scenarios. While crop production increases are in part the result of changes in yields due to technology and climate, production of meat drives large increases in pasture areas. Overall, more land is projected to be converted to pasture than to cropland. Despite the sharp increase in production, domestic demand for meat in the Lake Victoria Basin is much higher than production by 2050 necessitating import and potentially affecting land use outside the region. The high demand for these products is driven by large projected population growth as well as changes in consumption patterns, which are the result of economic growth and associated increases in income, living standards and aspirations under all future scenarios.

Expanding protected areas can lead to the displacement of land use and its impacts on biodiversity and ecosystem functions to unprotected areas. This effect can be seen in this study for forests as well as for overall areas of biodiversity importance. In the case of forests, restricting land conversion in protected areas leads to slightly greater overall loss of forest area. This is because there is relatively more forest area outside protected areas, and therefore conversion of this land leads to more forest loss overall. In all five countries, large amounts of forest are already expected to be lost to agricultural uses and even more land would be required if yields were to increase at a lower rate than under the considered scenarios. Areas within the Lake Victoria Basin where baseline values for biodiversity and ecosystem services are highest are also those with the highest projected losses, as natural land cover is converted to agriculture and urban expansion such as in western Uganda and towards the north of Lake Victoria. Increases in commodity provisioning functions often trade-off with regulating and wild provision functions. When considering planned infrastructure and potential future extractive industry activities, the watersheds adjacent to Lake Victoria appear to be particularly threatened, though the whole basin will likely be affected.

Conclusions

The strong effect of population increase under all future socio-economic scenarios, highlights the urgent need to increase production on existing land for both crops and livestock under any future scenario, as well as the need to continue addressing population growth and global consumption patterns. The results also show that this needs to be accompanied by appropriate incentives and regulation to avoid expansion into forest or grass/shrubland areas that hold and provide important biodiversity and ecosystem functions, especially outside protected areas. Moreover, intensification of agriculture may lead to other unintended negative consequences for the environment and should therefore be carefully managed.

Impacts of climate change on crop yields play a key role in determining the amount of land needed to meet the demands of a growing population. Yet, climate change projections are extremely uncertain and the potential impacts on crop yields are hard to predict. Any future yields lower than those projected in this study would be particularly devastating in the Lake Victoria Basin.

The study showed that there are areas within the Lake Victoria Basin that are likely to be under higher pressure than others in the future. It is important that these areas are acknowledged by decision makers and further action is taken to better understand local circumstances and opportunities to avoid or mitigate some of the potential negative impacts.

Analysis of different conservation policy options showed that the role of protected areas in the protection of biodiversity and ecosystem services should be carefully assessed in a regional context. Increasing protection in one area may lead to loss of unprotected critical habitat elsewhere. It also showed the importance of using a spatially explicit approach to consider potential trade-offs and linkages among land uses.

The results show that it is important and possible to identify broad spatial patterns of likely threats and pressures under different socio-economic futures. The analysis of these patterns, where they are consistent and where they differ, can support the development of policy to achieve its intended outcomes in an uncertain future. This analysis generates and illustrates broad patterns and highlights areas of concern, any decision-making process that uses these results should make sure that more local variations and impacts are taken into account.

Access to and capacity to use spatially explicit information to understand potential implications of future socio-economic development on agriculture or conservation policy is essential to help develop more robust and "future proof" policies. A guidance document accompanies this report, setting out the approach and how it can be used to inform the development of more robust policies, and ultimately in making more informed choices that balance conservation and development.

1 Introduction

The global human population is projected to reach 9.8 billion by 2050 and already one in nine people go to bed hungry (UN DESA, 2017, FAO *et al.,* 2014). Africa's population is expected to double by 2050 (Gerland et al. 2014). The increased demand for food (a projected rise of 60% globally by 2050 based on 2005/2007 levels) will be exacerbated by increasing prosperity in some regions which will be associated with increased demand for protein (Alexandratos, 2009, Alexandratos & Bruinsma 2012). Meanwhile, to reduce their carbon emissions, many countries are aiming to meet an increasing percentage of their energy needs from renewable sources, including bio-energy, leading to a projected 90% rise in demand for some bio-energy feedstocks by 2018 (OECD-FAO, 2008). Together, these rising demands represent an enormous need for increased agricultural production. Between 1965 and 2005, global food production has doubled with only a 12% increase in global cropland area, largely through improved crop breeding and agricultural intensification (Foley *et al.,* 2005). However, this intensification may have negative impacts on the environment and natural resources. Around 30% of agricultural lands are now degraded and annual increases in cereal crop yields in the major 'bread-basket' regions are slowing (Foley *et al.,* 2005; Ray *et al.,* 2012). In Africa, crop yields have stagnated since the 1970s, though there is evidence that large increases in yield could be achieved even with limited investment (Ray *et al.,* 2012).

Over the coming decades, society will have to balance competing needs for land to feed the growing human population, provide resources and energy to satisfy accelerating human consumption, slow global warming and reduce the rate of loss of ecosystem services and biodiversity. Decision makers need to balance different demands on land and take into account potential changes in these demands in the future, for example due to projected population growth, urbanisation and climate change, in particular in Sub-Saharan Africa. At the same time, many other and more uncertain factors may influence future policy outcomes, such as globalisation, commodity markets, governance regimes and regional integration. Therefore, implications of demands upon land for biodiversity and ecosystem services may vary through time and space. It is crucial that decision makers have access to spatially explicit information and analyses on the potential effects of different trajectories of human-induced landscape change, but also that they develop policies that are robust and adaptable so they achieve their intended outcomes under unpredictable future circumstances.

This technical report is an output of UNEP-WCMC's project on *Engaging stakeholders in using scenarios of land use change due to agricultural commodity development in the Lake Victoria Basin* funded by the John D. and Catherine T. MacArthur Foundation. The project has two major components:

1) Provide analyses and baseline data to support decision-making in relation to the potential future impacts of major commodity developments on biodiversity in short-term and long-term planning in the Lake Victoria Basin.
2) Develop guidance on how such information can be used to support the development of more robust policies, and ultimately making more informed choices balancing conservation and development.

The Lake Victoria Basin supports important biodiversity and ecosystem services which in turn support the livelihoods of millions of people. The Basin is home to numerous terrestrial and freshwater Key Biodiversity Areas[1] that include unprotected wetlands and forest habitats, as well as protected forest reserves and national parks covering various habitat types. These habitats host critically endangered and vulnerable birds and mammals such as Sharpe's Longclaw, Shoebill, black rhino and mountain gorilla. In addition, its forests play an important role in carbon sequestration and storage and provide timber, fuel wood, building materials and medicine. Wetlands and other ecosystems regulate flooding and support soil formation. Cultural services are primarily linked to tourism and education but also include spiritual and existence values (CEPF, 2012). Lake Victoria is the largest freshwater body in Africa; it hosts the largest freshwater fisheries on the continent and provides an important transport system for the East African region.

In recent years the lake is increasingly under threat from increased fishing pressure, nutrient inflows and de-oxygenation, inorganic pollution, invasive species and unsustainable use of wetlands and forests in the catchment resulting in siltation and eutrophication of the lake. These impacts are likely to increase under the rapid developments in the region. Population is increasing rapidly (e.g. 3% per year in Uganda), as well as access to commodity markets (e.g. through infrastructure development), which will likely lead to further degradation of ecosystems (Mapendembe & Sassen, 2014). The watershed is also the location of rapid developments in the exploration and exploitation of oil and gas. The increasing competition for land and resources to meet the growing demands for food and other commodities leads to increased pressure on biodiversity and ecosystems in the Lake Victoria Basin (BirdLife International, 2011).

This report aims to be a two-fold source of information for national and regional stakeholders who influence agricultural and conservation policy and planning in the Lake Victoria Basin. Such stakeholders may include government ministries, relevant regional authorities such as the Lake Victoria Basin Commission, the Nile Basin Authority and the East African Community, as well as other stakeholders, such as civil society organisations advocating for more sustainable and informed policies or researchers who may use the results or data to target areas for further study. It presents and applies an analytical framework to assess and visualise likely future impacts of land use change on biodiversity and ecosystem functions under different future socio-economic scenarios for East Africa and discusses potential implications of the results for policy. The document does not aim to provide specific policy recommendations for agricultural development in the Lake Victoria Basin. Rather, it aims to provide plausible future contexts under which such development may take place in order to balances both agricultural development and biodiversity conservation within policy formation. A companion document sets out guidance on how such scenario analysis can be used to support the development of more robust policies, and to ultimately make more informed choices in an uncertain future.

The report is structured as follows: Chapter 2 sets out the approach used, including the conceptual framework, the key criteria guiding the analysis, the modelling framework, the scenarios and the methods for quantifying land use change, biodiversity, ecosystem functions and for assessing pressure and threat. Chapter 3 presents and discusses the results of the analyses. Finally, Chapter 4 highlights general patterns and lessons from the scenario analyses.

[1] http://www.keybiodiversityareas.org/home

2 Methods

2.1 Conceptual analysis framework

The spatial analysis framework seeks to answer the following overarching question:

Where are the current and future potential priorities for biodiversity and ecosystem services in relation to potential threats from land use change within the Lake Victoria Basin?

In order to answer this question, a conceptual analysis framework was designed that can be used to explore the impacts of plausible socio-economic scenarios on biodiversity and ecosystem services. A key component of this framework is the spatially explicit assessment of changes in the landscape driven by these scenarios. These landscape changes were projected using a land-use change model and are used as the basis to assess current and future states of biodiversity and ecosystem function, and of pressures on biodiversity. Current and future states can then be compared to assess change (Figure 1).

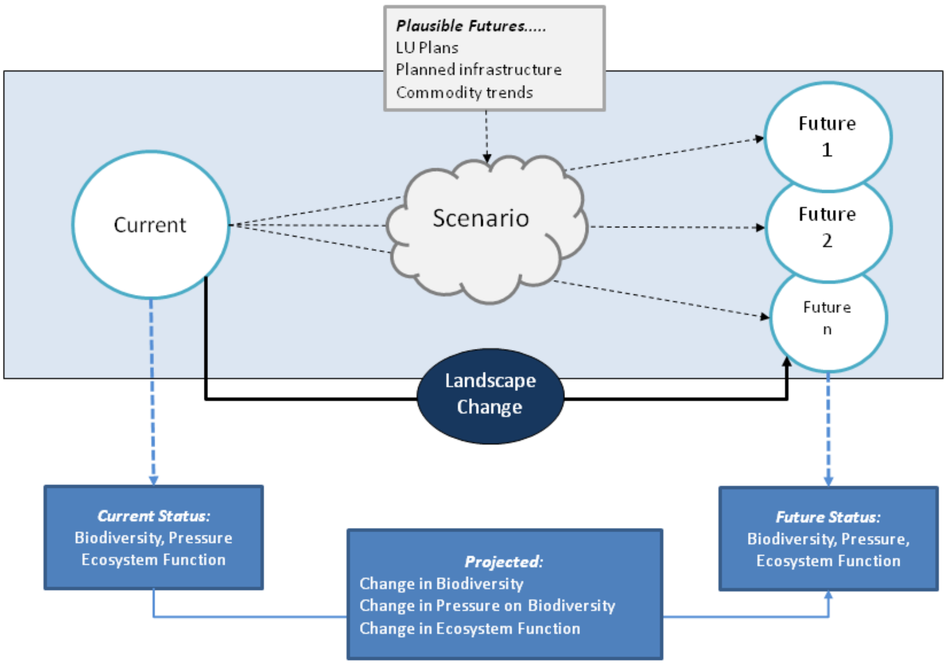

Figure 1: Conceptual analysis framework. Different socio-economic scenarios are characterised through changes in the landscape. Blue boxes represent the analysis of impacts for current and future status, allowing for assessment of changes between these two states (Source: van Soesbergen & Arnell, 2015)

2.2 Study area and scale of analysis

The Lake Victoria Basin covers parts of five countries: Tanzania, Kenya, Burundi, Rwanda and Uganda (Figure 2). The study region is subdivided into watersheds and these watersheds are used as the units of analysis, i.e. all results show single values for each watershed. This approach was used as the watershed units are an appropriate scale for the assessment of transboundary impacts at regional level as well as for the identification of areas for local action. Furthermore, by aggregating the impact results to watersheds some of the spatial uncertainty deriving from the modelling exercise is accounted for: this study combines scenarios with spatially explicit land-use change modelling and an analysis of impacts, each of which has some uncertainty attached which is propagated throughout the analysis framework (Van Soesbergen & Arnell, 2015).

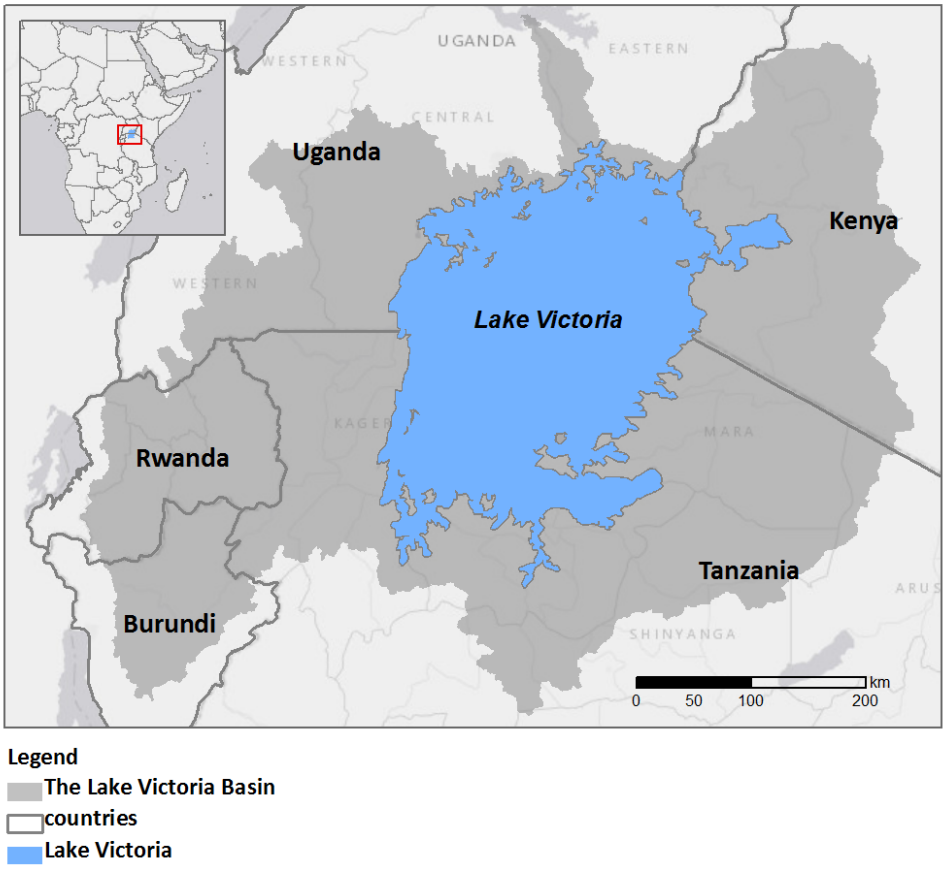

Figure 2: Lake Victoria and extent of Lake Victoria Basin covering parts of five countries.

2.3 Focal questions

The analysis framework focuses on biodiversity, pressure on biodiversity and ecosystem functions. These are addressed through the following questions:

- ***Biodiversity:*** *what is the estimated importance of each watershed for biodiversity, relative to the whole Lake Victoria Basin?*
- ***Pressure on biodiversity****: what is the pressure on biodiversity in each watershed, relative to the Lake Victoria Basin?*
- ***Ecosystem function:*** *what is the estimated importance of each watershed for potential ecosystem function provision, relative to the Lake Victoria Basin?*

2.4 Modelling framework

The study was carried out using socio-economic scenarios for the East Africa region (described in section 2.6) which were then quantified in terms of national demand for food and other agricultural commodities, yields and production using the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT; Robinson *et al.*, 2015) developed by the International Food and Policy Research Institute (IFPRI). The outputs from the IMPACT model where then used by the LandSHIFT land use change model developed by the Center For Environmental Systems Research at Kassel University (Schaldach *et al.*, 2011) to spatially allocate agricultural production within the study area. Simulations were done at high resolution (~1km). The model results were then used to assess impacts on biodiversity and ecosystem function for all watersheds within the Lake Victoria basin (Figure 3). Both models are described in more detail in the sections below. Furthermore, a freely available web-based tool (http://macarthur.unep-wcmc.org) was developed that can be used to explore all the results for the different scenarios and analyses within each study region. This tool is described in more detail in Appendix V.

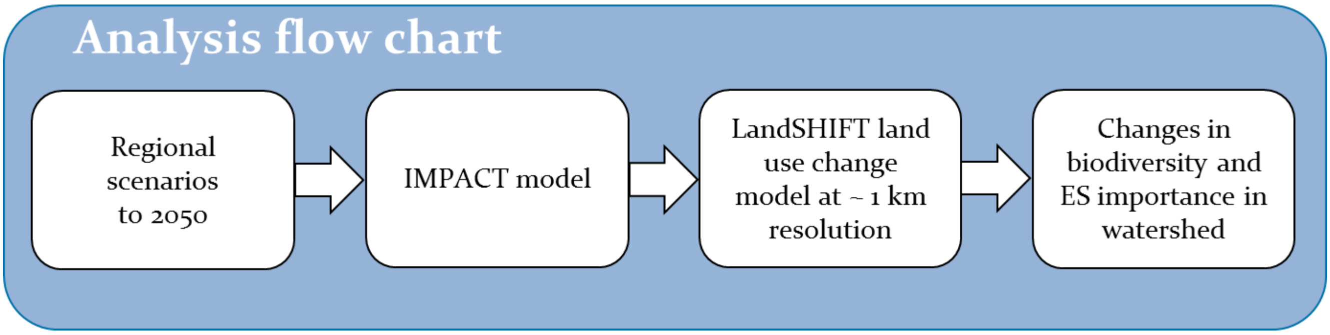

Figure 3: Modelling framework flowchart.

2.5 Scenarios

The regional scenarios used in the analysis were developed in collaboration with the Climate Change Agriculture and Food Security research program of the Consultative Group on International Agricultural Research (CGIAR CCAFS). This research program aims to develop plausible qualitative and quantitative future scenarios that can be used to explore consequences of socio-economic as well as governance assumptions and resulting impacts on food security, the environment and livelihoods. Scenarios were developed for different regions, each covering several countries (i.e. East Africa, South Asia, Southeast Asia and South America).

The CCAFS scenarios for the East Africa region were developed in 2010 and 2011 through four multiple-stakeholder workshops with participants from Kenya, Tanzania, Ethiopia, Uganda, Rwanda and Burundi as well as regional actors. Four scenarios were developed, framed by two main drivers of change: governance (reactive or proactive) and level of regional integration (fragmentation or strong integration). The stakeholders considered these dimensions to be key but highly uncertain drivers relevant for food security, environments and livelihoods for the region. The drivers were selected through a participatory identification and prioritisation process. The scenario building process started with a vision for 2030 under each scenario and then the narratives describing the trends and events from 2010 to 2030 were developed (Vervoort *et al.,* 2013). To support quantitative modelling of the scenarios, the workshop participants also provided semi-quantitative assessments for what they considered major drivers of change under the different scenarios, as well as the assumptions behind those assessments. The following drivers were included: population, gross domestic product, production costs, crop yields, crop production systems, livestock numbers, yields and production systems and finally land-use change emissions tax. The most influential drivers of change for the 2010-2030 period were perceived to be population and climate change.

The final four scenarios are summarised below with extended narratives in Appendix I. A key component in the storyline of all four scenarios is an extreme weather event, namely a severe drought in 2020. These scenarios and the process of their development are described in more detail in Vervoort *et al.* (2013). The scenarios were named by the scenario development workshop participants.

Industrious Ants. This scenario is characterised by proactive governance, and high regional integration with a wide range of benefits for food security, environments and livelihoods. However, there are difficult international relations, a costly battle with corruption and challenges posed by being competitive with crops and products aimed at domestic markets.

Herd of Zebra. In this scenario, there is an economic boom where regions reach out to international markets. However, the scenario is not economically sustainable, with trade-offs between food security and the environment, dependency on service and industrial markets, and new vehicles for corruption weakening effectiveness.

Lone Leopards. This scenario is characterised by visionary actions carried out by individual organisations and initiatives facilitated by governments. It is a world of winners and losers, with uncoordinated trade and shared resources, instability, selfish behaviours and corruption preventing coordination.

Sleeping Lions. This scenario is characterised by massive public mobilisations, international investments, informal trade, a personal sense of community and psychological resilience. Governments in 2030 act in self-interest, allowing rein of foreign interests and making money through crises. It is a scenario with no win-win situations, latent capacity and wasted opportunity. Revolutions are common and lead nowhere.

2.6 Quantification of scenarios - the IMPACT model [version 3]

IMPACT V3 (Robinson *et al*., 2015) is a network of linked economic, water, and crop models, built around a global partial equilibrium multi-market economic model. IMPACT focuses on the agricultural sector and is developed to "examine alternative futures for global food supply, demand, trade, prices, and food security" with a particular focus on developing countries (model documentation and output data available at https://www.ifpri.org/program/impact-model).

The model is constantly being updated to include more agricultural commodities (62 in the current version of the model) which include oilseeds (groundnuts, soybeans and rapeseed), cotton and major dry land grains and pulses, as well as livestock products, and processed commodities like food oils and sugar. Cash crops such as coffee and cacao are also considered in the model. These commodities are key to understanding the drivers behind the projected growth of global oil, meat and milk demand. A full list of commodities modelled by IMPACT is given in Appendix II.

The water simulation module (IWSM) of IMPACT balances water availability and use within various economic sectors. In order to incorporate water availability at the basin level, the model uses so-called 'food producing units' or FPU's as its unit of analysis. These FPU's are a combination of 159 countries with 154 water basins, thus ensuring that climatic and hydrologic variations within regions are accounted for within hydrologically defined basins. Within the model, the supply and demand of water and crop production are first assessed at the basin scale and crop production is then summed to the national level at which food demand and trade are modelled.

Climate change affects yields through two mechanisms. Firstly, the effects of changes in temperature and precipitation are incorporated through a link with the crop-simulation model DSSAT (Decision Support System for Agro-technology Transfer) which is able to assess climate change effects and CO_2 fertilisation for wheat, rice, soybeans, groundnuts (all C3 pathway crops) and maize (C4 pathway). Other crops modelled in IMPACT are assumed to react similarly to climate change effects within the same geographical region and metabolic pathway (C3 or C4). In addition to the metabolic pathways, biological similarity is also taken into account. E.g. for pulses average values are calculated based on data for groundnuts and soybeans which are also nitrogen fixing. The second pathway of yield impacts through climate change is through the variation in water availability for agriculture as calculated by the water models that link with IMPACT, which calculate water supply relative to crop demand accounting for differences among crops and varieties. Calculated yield shocks are then incorporated in the IMPACT model with an impact on year-to-year crop yield.

In addition to the biophysical effects, modelled yields include economic feedbacks. These economic effects simulate producers' response to changes in productivity and commodity markets, and include changes in crop allocation, and application of inputs (e.g. fertilisers) in response to changes in relative crop suitability and prices (Mason d'Croz *et al*., 2016).

Initially, the quantification of the scenarios with the IMPACT model was completed up to 2030, but later extended to 2050 for this study.

Drivers

Population projections in the model follow the medium variant growth projections from the UN population database 2010 revision (United Nations Population Division, 2011). Gross Domestic Product (GDP) projections follow the narrative assumptions of the scenarios and are based on historic GDP with future projections constrained in a plausibility envelope derived from a study on Food Security, Farming and Climate change to 2050 (Nelson *et al.,* 2010). Crop yields in the model follow technical improvement assumptions in the scenarios. In terms of cropping system, the model distinguishes between irrigated and rain fed systems. Livestock yields are driven by an exogenous yield trend. Furthermore, increased drought periods were assumed in all scenarios, with a severe drought occurring in the 2020–2022 period. More detail on these drivers and their underlying assumptions can be found in Vervoort *et al.* 2013.

Assumptions and limitations

IMPACT is a partial equilibrium model which focuses on the agriculture sector, and holds the rest of the economy as exogenous to the model. This approach allows for a more detailed representation of the agricultural sector, but in so doing loses potential feedbacks from other sectors. A key assumption of this type of economic model is that people will seek to maximise utility, either in financial or commodity gains (Evans *et al.,* 2001) which is not always the main factor affecting land allocation decisions (Walker, 2004).

2.7 Landscape changes - the LandSHIFT model

The LandSHIFT model framework (Schaldach *et al.,* 2011) is a tool for medium-term scenario analysis (20-50 years) and assessment of environmental impacts of land-use change and is developed by the Center for Environmental Systems Analysis of Kassel University, Germany. The model simulates spatial-temporal dynamics of settlement, crop cultivation and livestock grazing. LandSHIFT is based on the concept of "land-use systems" (Mather, 2006) as it couples model components representing anthropogenic and environmental systems.

The model is built around two main components, a land-use change (LUC) module and a productivity module. The productivity module calculates crop yields and net primary productivity (NPP) of grasslands which are important inputs to the land-use decisions of the LUC module. Land-use change is then simulated using demand for land-intensive commodities and supply defined by the local biomass productivity in a specific cell. Productivity is influenced by climate change and technological changes. The model requires input from driving variables that describe the socio-economic and agricultural development of a country as well as micro-level variables (grid-scale) that describe local landscape characteristics (i.e. baseline land use, urban areas, protected areas, roads etc.). Outputs from the model consists of time-series of maps of land-use type as well as population and livestock densities. All output maps are produced for each time-step which is fixed at five years. Macro-level input data (i.e. socio-economic data and agricultural production data) needs to be at country scale while micro-level data can be specified for sub-regions (model documentation and output data are available at https://www.uni-kassel.de/einrichtungen/en/cesr/research/projects/finished/landshift.html)

LandSHIFT can be run at different resolutions and with different base land-use data. The choice of input land-use data determines the resolution of the output data. For this study, the Global Land Cover dataset for the year 2000 (GLC2000) was used (Bartholomé & Belward 2005). This dataset provides high resolution (30 arc seconds or ~ 1km); harmonised land cover for the globe based on satellite remote sensing from the SPOT-4 VEGETATION sensor. GLC2000 uses the Food and Agriculture Organisation (FAO) Land-Cover Classification System (LCCS) with a total of 23 main land-use types classified. 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). LandSHIFT computes all land-cover types from the base land-use dataset and sub-divides arable land classes into 20 different crop types (Table 1).

Table 1: Land-use/cover classes in GLC2000 and LandSHIFT.

GLC2000 code	GLC 2000 description	LandSHIFT code	LandSHIFT description
1	Tree cover, broadleaved, evergreen	1	Tree cover, broadleaved, evergreen
2	Tree cover, broadleaved, deciduous, closed	2	Tree cover, broadleaved, deciduous, closed
3	Tree cover, broadleaved, deciduous, open	3	Tree cover, broadleaved, deciduous, open
4	Tree cover, needle-leaved, evergreen	4	Tree cover, needle-leaved, evergreen
5	Tree cover, needle-leaved, evergreen	5	Tree cover, needle-leaved, evergreen
6	Tree cover, mixed leaf type	6	Tree cover, mixed leaf type
7	Tree cover, regularly flooded, fresh and brackish water	7	Tree cover, regularly flooded, fresh and brackish water
8	Tree cover, regularly flooded, saline water	8	Tree cover, regularly flooded, saline water
9	Mosaic: tree cover/other natural vegetation	9	Mosaic: tree cover/other natural vegetation
10	Tree cover, burnt	10	Tree cover, burnt
11	Shrub cover, closed-open, evergreen	11	Shrub cover, closed-open, evergreen
12	Shrub cover, closed-open, deciduous	12	Shrub cover, closed-open, deciduous
13	Herbaceous cover, closed-open	13	Herbaceous cover, closed-open
14	Sparse herbaceous or sparse shrub cover	14	Sparse herbaceous or sparse shrub cover
15	Regularly flooded shrub and/or herbaceous cover	15	Regularly flooded shrub and/or herbaceous cover
16	Cultivated and managed areas	16	Cultivated and managed areas
17	Mosaic: cropland/tree cover/other natural vegetation	17	Mosaic: cropland/tree cover/other natural vegetation
18	Mosaic: cropland/shrub or grass cover	18	Mosaic: cropland/shrub or grass cover
19	Bare areas	19	Bare areas
20	Water bodies	20	Water bodies
21	Snow and Ice	21	Snow and Ice
22	Artificial surfaces and associated areas	22	Artificial surfaces and associated areas
23	Irrigated agriculture	23	Irrigated agriculture
-	n/a	99	Set-aside
-	n/a	100	Default crop
-	n/a	101	Cassava
-	n/a	102	Temperate cereals
-	n/a	103	Tropical cereals
-	n/a	104	Cotton
-	n/a	105	Fruits
-	n/a	106	Groundnuts
-	n/a	107	Maize
-	n/a	108	Millet
-	n/a	109	Oil crops annual
-	n/a	110	Oil crops permanent
-	n/a	111	Pulses
-	n/a	112	Rice
-	n/a	113	Temperate roots and tubers
-	n/a	114	Tropical roots and tubers
-	n/a	115	Sorghum

-	n/a	116	Soybeans
-	n/a	117	Stimulants
-	n/a	118	Sugarcane
-	n/a	119	Vegetables
-	n/a	120	Wheat
-	n/a	200	Pasture
-	n/a	201	Range land

The land-use change module in LandSHIFT uses a transition matrix which defines which land-use types can turn into other land-use types. For instance, urban land can never turn into arable land, whereas the reverse is possible. Constraints to conversion can also consist of policy decisions or laws prohibiting the conversion of, for instance, protected areas. All cells are assigned a land-use type on the basis of a preference ranking of suitability for a given land-use type. The preference ranking is computed using a multi-criteria analysis with weighting factors which determine the importance of individual factors (e.g. slope, roads, population density). Suitability factors and constraints to conversion are based on values from scientific literature, e.g. thresholds of population density before a cell is categorised as an urban land-use.

A set of key variables in the model are used as crop specific correction factors. These factors match country-level crop production (as reported by FAO statistics or from the driving economic model such as IMPACT), with modelled crop production. Modelled crop production is calculated from a baseline simulation which uses the sum of total modelled production of each crop type from the initial land-use/land-cover map. These factors can be used to account for agriculture management alternatives such as double-cropping which are not explicitly modelled in LandSHIFT.

Climate change is incorporated in the model through the productivity module. This module consists of the dynamic global vegetation model LPJmL (Bondeau *et al.,* 2007) which calculates crop yields for all crops considered in LandSHIFT under rainfed and irrigated conditions as well as NPP for pasture. LPJmL specifically simulates sowing dates, crop phenology, crop growth and carbon allocation at a daily time step taking into account climate variables such as precipitation and temperature which can be based on different climate alternatives. All model runs in this study were carried out for a climate scenario based on the Representative Concentration Pathways (RCPs, Moss *et al.,* 2010) using a global circulation model (GCM) based on the 5th assessment report of the Intergovernmental Panel on Climate Change (IPCC). The climate scenario used is the RCP 8.5 modelled using the IPSL -CM5A-LR — The Institut Pierre Simon Laplace's Earth System Model climate model (Dufresne *et al.* 2013). RCP 8.5, developed for the 5th Assessment report of the IPCC, has the most extreme emission pathway of all RCPs and assumes a continued rise in emissions throughout the 21st century and a mean global warming increase of 2˚C by 2050 (Riahi *et al.,* 2011). This GCM-RCP combination was chosen to be consistent with available results from IMPACT which were modelled using the same combination of climate model and emission scenario.

For this study, all micro-level landscape characteristics data are based on global datasets (Table 2)

Table 2: Spatial micro-level data used in LandSHIFT for model initialisation.

Model variable	Dataset name	Native resolution	Temporal coverage	Source
Land use/cover	GLC2000	30 arc- seconds	ca 2000	Bartholomé, E., & Belward (2005)
Population density	GRUMP	30 arc-seconds	ca 2000	CIESIN & CIAT (2005)
River network density	HydroSHEDS	15 arc seconds	2004	HydroSHEDS rivers of Africa, Asia and South America. Lehner *et al.* (2006)
Road infrastructure	gROADSv1	30 arc seconds	1980-2010	CIESIN (2013)
Protected Areas	Wold Database on Protected Areas	shapefile	2013	UNEP-WCMC/IUCN
Key Biodiversity Areas	World Bird and Biodiversity areas database	shapefile	2013	BirdLife International

Conservation policy options

To explore the potential effect of changing conservation policy options on spatial trade-offs in land conversion, the model was run under three different assumptions (for each scenario): a) a strict conservation policy, where all existing protected areas (based on the World Database of Protected Areas, IUCN & UNEP-WCMC, 2013) within the study region are restricted for conversion of land use, b) no-conservation policy, where there are no restrictions on conversion of protected areas (i.e. the same rules apply within protected areas as outside protected areas) and c) an extended conservation policy, whereby in addition to existing protected areas, broader areas globally considered to be Key Biodiversity Areas are assumed to be protected as well (i.e. no conversion allowed within Key Biodiversity Areas). This last scenario was run to better understand spatial trade-offs in land conversion under different protected area management regimes.

Assumptions and limitations

While the LandSHIFT model can be run at various grid resolutions, for this study the model was applied at 30 arc seconds (~1km). The model runs were carried out at the resolution of the GLC2000 basemap for land use/land cover (1km). Since the spatial resolution of the LPJmL crop model is 5 arc minutes (10km) not all parameters are fully resolved at this resolution. However, in the impact analysis for biodiversity and ecosystem functions, all crop types are aggregated within the watershed unit of analysis and so this does not have an effect on the final impact results.

Furthermore, since the model uses dominant crop types the cropping pattern can seem artificial in comparison with approaches that assign fractional shares of different crops to grid cells. Again, while this would be an issue if individual crop areas need to be assessed within watersheds, for the impact analysis in this study the overall expansion of cropland under scenarios is more relevant.

There are very few land-cover products that have been consistently assessed at multiple points in time. The GLC2000 dataset is compiled using remote sensing data for roughly the year 2000. While this provides a good baseline, it means that it is not possible to validate the land-use change model with 'observed' data at a later point in time (i.e. after one or two time-steps) using a dataset which is compiled using the same algorithms and methods. The accuracy of GLC2000 land-cover types for different regions is found to be variable. Studies for East Africa have shown a good validation for a number of land-cover types for the East Africa region (Herold *et al.*, 2008). Overall the GLC2000 dataset provides adequate accuracy for this study.

2.8 Biodiversity metric

Biodiversity was assessed for a baseline (modelled for 2005) and future (2050) time periods, using a novel index for biodiversity. A further index was developed to calculate change between these periods. Biodiversity data were obtained from the IUCN Red List spatial dataset (http://www.iucnredlist.org/) and an established method of linking species' habitat preferences to land-use/land-cover types was used. Aspects of this approach are based on Buchanan *et al.* (2011), who used an impact metric based on range-rarity (weighted endemism) and IUCN species range data refined by land cover.

IUCN Red List spatial data: selection criteria

All available species range data from the IUCN Red List (IUCN, 2014) were collated for vertebrate classes that have been comprehensively assessed: aves (birds), amphibia (amphibians) and mammalia (mammals). It is important to note that these data provide the Extent of Occurrence (EOO) of each species, which is defined as 'the area contained within the shortest continuous imaginary boundary which can be drawn to encompass all the known, inferred or projected sites of present occurrence of a taxon' (IUCN, 2014a). Therefore, unsuitable or unoccupied habitats may be included in these ranges. The dataset was filtered to include those ranges listed as extant, native or reintroduced, and with seasonal attributes listed as either resident, resident breeding or resident non-breeding. This step removed ranges of species that were extinct or probably extinct, where a species has been newly introduced (i.e. invasive), or is likely present for only a brief period, such as on a migratory passage. From species that remained, all further analyses were carried out on those whose ranges intersected the study region and for which IUCN habitat preference data were available. Each range polygon was simplified to remove unnecessary detail (i.e. vertices within 10m of each other), thus improving processing speed.

IUCN habitat preferences

Additional non-spatial data on IUCN Habitat preferences were compiled which list each species with their IUCN habitat classes, based on expert opinion and literature (IUCN, 2014a). A small number of species (~0.4%) were lacking such data and were excluded from analysis. Only habitat categories classed as suitable were included in the analysis, thus excluding marginal habitats as these were less relevant to the aims of the study. Within the suitable habitat category no distinction was made for those classed as major habitats, as only half the species had habitats in this sub-category.

IUCN-LandSHIFT Crosswalk

From the list of suitable habitats for each species, a corresponding list of suitable LandSHIFT land-use types was derived using a crosswalk table based on Foden *et al.* (2013). This aims to provide a link between species habitat preferences and modelled land use. This crosswalk was originally created to allow the refinement of IUCN species' ranges by linking IUCN habitat classes to the Land-Cover Classification System (LCCS), the classification system used by Global Land Cover 2000. Although GLC2000 was used as a basis for modelling, the LandSHIFT model has additional classes for crop, pasture and set-aside areas, thus a number of additional links were added to these classes (see Appendix IV). The spatial linkage between a species range and modelled land use was based on the total area of a species range overlapping with the watershed and the area of suitable land cover in that watershed (Figure 4). The final equations used to calculate the biodiversity importance indices are outlined in the section below.

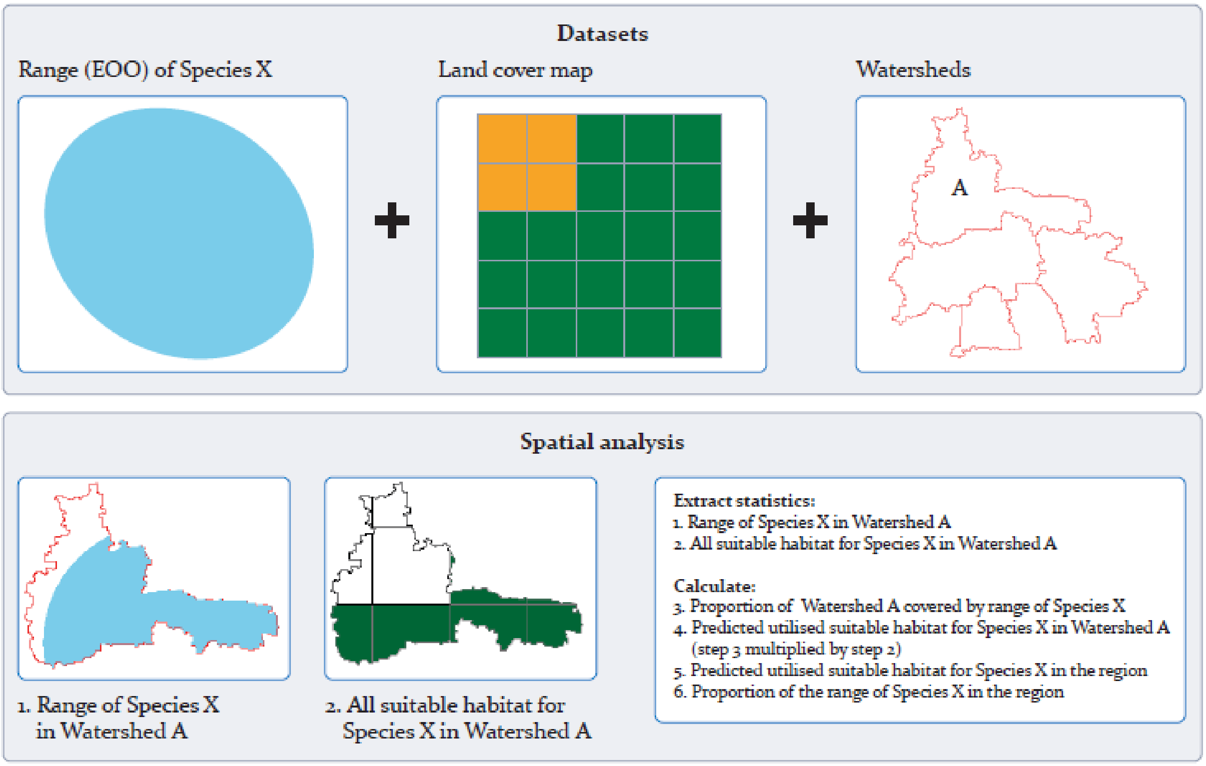

Figure 4: Workflow for mapping biodiversity in watersheds. Data on species range (blue) was combined with modelled land-cover data and watershed polygons. The areas of species X's range (1) and suitable habitat (2) overlapping with watershed A were extracted. The proportion of watershed A covered by species X (3) was calculated and multiplied by suitable habitat for the species, to derive the predicted utilised suitable habitat in Watershed A (4). The area of predicted utilised suitable habitat for species X in the region (5) and proportion of the range of species X in the region (6) were also calculated.

Biodiversity importance index

The relative biodiversity importance in a given watershed is calculated as the sum of the area of predicted utilised suitable habitat within the watershed, divided by the total area of predicted utilised suitable habitat within the region (i.e. summed over all watersheds) multiplied by the relative overlap of that species range with the region to the total extent of occurrence of that species (Equation 1). The second term in the equation was introduced to give more weight to species that are endemic to a region.

Equation 1:

$$\text{importance}_{wi} = \left(\frac{H_{wi_{t_0}}}{\sum_{1}^{w} H_{wi_{t_0}}} \right) \times \frac{R_i}{EOO_i}$$

With H: Area of predicted utilised suitable habitat for a species (i) in a watershed (w) in the baseline situation (T_0) OO_S: The species total extent of occurrence, R_S: Overlap of the EOO with the region

Equation 1 describes how to calculate the importance for a single species in the baseline situation. In order to calculate the importance for all species (s) equation 1 is summed over all species (Equation 2).

Equation 2:

$$\text{importance}_{ws} = \sum_{1}^{i} \left(\left(\frac{H_{wi_{T_0}}}{\sum_{1}^{W} H_{wi_{T_0}}} \right) \times \frac{R_i}{EOO_i} \right)$$

The above equations can be used to assess the relative importance of watersheds for single or multiple species, for either the baseline or a future situation (states).

To assess the change in biodiversity importance for a species between the baseline and a future situation (i.e. under a given scenario) the relative change in importance was assessed relative to the importance for that species in the baseline situation and summed over all watersheds (i.e. the region (r)) (Equation 3). This is necessary since the state situations are relative to the total summed importance at that time-period (baseline or future) and thus direct comparisons between these state situations would not be a true reflection of change.

Equation 3:

$$\Delta\text{importance}_{ir} = \sum_{1}^{w}\left(\left(\frac{H_{wi_{T_1}} - H_{wi_{T_0}}}{\sum_{1}^{w} H_{wi_{T_0}}}\right) \times \frac{R_i}{EOO_i}\right)$$

With T_1 the future period

Finally, to assess the change for all species or groups of species in a watershed, the above equation is summed over all species:

Equation 4:

$$\Delta\text{importance}_{ws} = \sum_{1}^{i}\left(\left(\frac{H_{wi_{T_1}} - H_{wi_{T_0}}}{\sum_{1}^{w} H_{wi_{T_0}}}\right) \times \frac{R_i}{EOO_i}\right)$$

Biodiversity importance (Equation 2) and change metrics (Equation 4) were calculated for watersheds for baseline and future scenarios. These results were based on all species combined and for subsets of i) birds, ii) amphibians, iii) mammals and iv) threatened species (i.e. Critically Endangered, Endangered or Vulnerable species, according to the IUCN Red List).

For this study, the biodiversity change metric was adapted slightly to focus on loss values (decreases) only, thus ignoring potential increases from land use conversion for those, typically generalist, species with affiliations to urban and/or agricultural areas. These were removed as they are of less relevance when attempting to highlight areas of concern for the conservation of biodiversity. To achieve this, positive values were filtered out when summarising across species for each watershed in Equation 4.

The decreases in biodiversity importance were normalised between scenarios to allow visual comparison of results for different scenarios. Normalised values ranged from 0 to -1, with -1 representing the highest decrease in all scenarios. Zero values represented areas of no change in importance. The resulting values were grouped into four classes based on natural breaks (Jenks) for data in the scenario-policy option combination with the highest loss (i.e., -1). Baseline results were grouped in five classes based on natural breaks.

Assumptions and limitations

- Biodiversity is represented by birds, amphibians and mammals. These are the only comprehensively assessed taxonomic groups by the IUCN Red List which have extent of occurrence maps available, and therefore this bias towards vertebrate classes is a reflection of the limited data available for such analyses.
- Species ranges were derived from the IUCN Red List database. IUCN Red List spatial data are compiled from a variety of sources and derived from a number of approaches such as consultation

with experts and interpolation from species localities. While these are generally believed to be the most accurate, there are some known uncertainties. In our methodology, the species range was used as the absolute location of a species occurrence and so it is assumed that species do not occur outside this range.

- Suitable habitat and species range overlap are both calculated at the scale of the watersheds. It is assumed that if there is suitable habitat within a watershed for a species, the species will be able to utilise the habitat even if there is no spatial overlap between the range and the suitable habitat. Since there are uncertainties in the spatial accuracy of both the modelled land-use types and the species ranges data, this is not an unreasonable assumption. However, this does depend on the size of the watershed.
- The biodiversity importance is based upon a combination of factors but primarily depends upon the area of species overlap with a watershed and the suitable habitat available (as well as factors related to the size of the species range globally). Therefore large watersheds are likely to score higher for biodiversity importance.
- The distribution of a species within the IUCN Red List range is assumed equal. In other words, the abundance of a species does not vary based on climate, altitude or land cover.
- The methodology assumes that all species are equal. No weighting is introduced to give more weight to individual species (e.g. different types of threat levels) as this would be too subjective. However, threatened species can be assessed separately as a group. It would be possible to introduce a weighting but this would require extensive expert consultation.
- The crosswalk linking species' preferred habitats with the LCCS classification was based on previous studies in which experts were consulted. It is assumed that these linkages and subsequent modifications to align habitat affiliations with additional LandSHIFT classes provide an accurate translation between the habitat classification systems.
- The biodiversity importance metric in this study is calculated using the total area of land-use types within the chosen unit of analysis (i.e. the watershed). Therefore this method does not explicitly assess spatial arrangement (i.e. fragmentation) of these land-use types within the study region which may be important for some species (Devictor & Julliard 2008).
- We assume that including species listed as native (or re-introduced) and extant, represent those species of relevance to conservation.

2.9 Ecosystem function metric

This study assesses the ecosystem functions that are provided by watersheds for baseline and future periods. Ecosystem functions in the context of this study are defined as the capacity of a landscape or specific land use type to provide ecosystem goods that can be (but are not necessarily) used by beneficiaries (services).

The assessment of ecosystem functions within watersheds is based on the premise that certain landscape characteristics contribute to the provision of certain ecosystem functions. The methodology followed in this study is based on a study by Kienast *et al.* (2009) which used literature and expert knowledge to identify binary links between specific land uses or other environmental properties and the landscape- or ecosystem functions these properties can provide. This method is well suited for the impact analysis in this study as changes in land use under future scenarios can directly be translated into changes in ecosystem function provision.

Various landscape functions and associated services belonging to four major groups are identified in literature (i.e., De Groot *et al.,* 2002; MA, 2005). These four groups are:

1) Production functions - the delivery of provisioning services;
2) Regulating functions - the delivery of regulating services;
3) Habitat functions - maintaining ecological structures and processes; and
4) Information functions - the delivery of cultural and amenity services.

This study only assesses production functions and regulating functions. Habitat functions are incorporated in the biodiversity metric, and for the information functions not enough data are available to assess these for the future period. Production functions are defined as the capacity of ecosystems to supply 'natural' products to people; this includes food, raw materials (i.e. fibre, fuel wood, timber) but can also include fossil fuels and hydro- and wind power. Regulating functions relate to the capacity of a landscape to influence environmental quality. This includes regulation of climate (e.g. through carbon fixation), natural hazard protection (e.g. flood prevention by forest and wetlands), water regulation, erosion prevention (e.g. forests) but also biological regulation such as pollination and pest control.

Binary link table

The binary link table developed by Kienast *et al.* (2009) links landscape characteristics with the ecosystem functions they can provide. This link table was originally developed for the CORINE (EEA, 2014) land-use dataset for the European Union. The binary link table was adapted to account for the different land-use classification used in this study (GLC2000/LandSHIFT) as well as specific landscape characteristics that are relevant for the Lake Victoria Basin. A translation between CORINE and the LCCS classifications is provided by Herold *et al.* (2009) and since GLC2000 is also based on the LCCS, this was used as a guide to match the different land-cover classes. The resulting binary link table is shown in Appendix III.

Landscape characteristics

Slopes

Steep slopes are difficult to cultivate and therefore often consist of natural land or forests, as such these areas are important for the wild provision and climate regulation ecosystem functions (Kienast, 2009). For each watershed, the area of steep slopes was calculated. Steep slopes were defined as having an inclination of 30% or more as defined by the FAO (FAO, 1984). Slopes were calculated from the Hydrosheds (Lehner *et al.,* 2006) elevation data (DEM) at 3 arc seconds resolution using the "calculate slope" tool in ArcMap v10.3. The area of steep slopes in each watershed was then linked to the wild provision and climate regulation ecosystem functions through the link table.

Cloud forests

Interception of wind-driven cloud water by cloud forests is important for the provision and regulation of water, accounting for up to 29% of the available tropical surface water balance (Mulligan & Burke, 2005). The extent of cloud forest occurrence was calculated using the FOGINT cloud forest model developed at King's College London (www.policysupport.org/fiesta-fogint). This physically based model calculates the occurrence of cloud forests as a pixel fraction for average climatic conditions using forest cover extent for the year 2010. Cloud forest was assumed at pixel fractions of 40% or higher based on Bubb & Das (2005) and Mulligan & Burke (2005). The final cloud forest extent map was then clipped with the LandSHIFT modelled forest occurrence data, for the baseline and future period to calculate the area of cloud forest within a watershed for 2005 and 2050. The total area of cloud forest in a watershed contributes to the wild provision and regulating function provision through the link table.

Ecosystem function importance index

The workflow applied in this study to map ecosystem functions for the study watersheds (Figure 5) is as follows: first, the area of each land-use type is calculated for each watershed. Then, the area of each additional landscape characteristic is calculated for each watershed. These areas are then combined with the binary relationship table to calculate the potential provision of ecosystem functions within watersheds as described below.

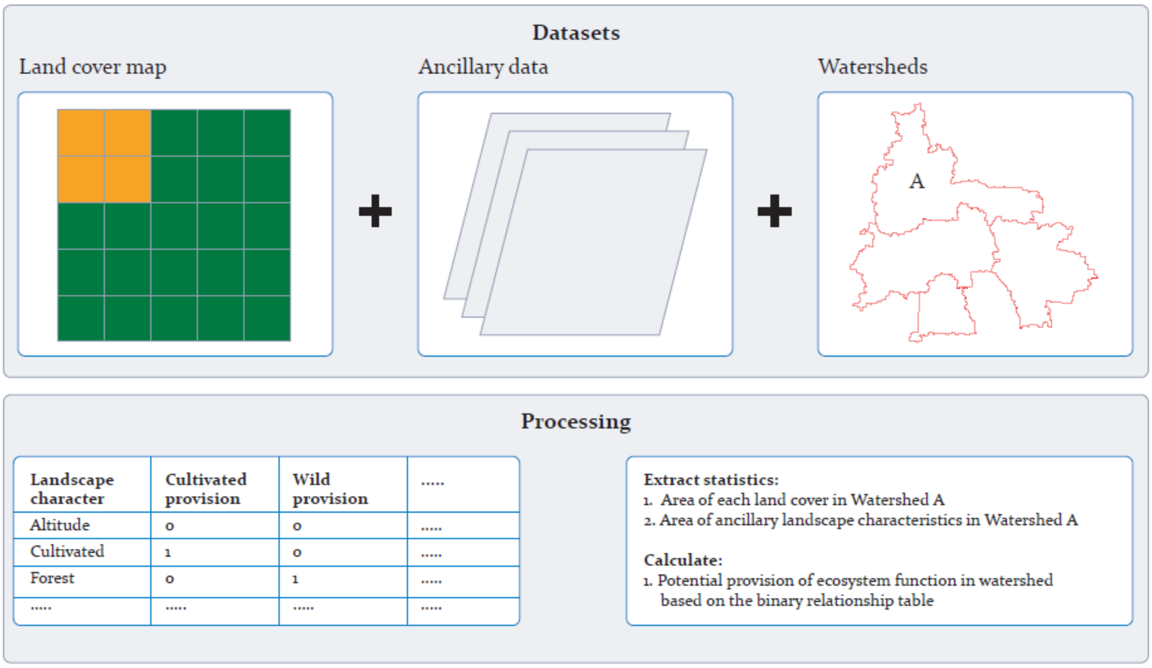

Figure 5: Workflow for mapping ecosystem functions in watersheds. Modelled data on land cover was combined with ancillary data and watershed polygons. The areas of different land-cover types and ancillary data (e.g. slopes) within a watershed were extracted and processed using a binary link relationship table.

The total relative importance of an ecosystem function (e.g. cultivated products) of a given watershed is calculated as the sum of all areas of contributing landscape characteristics to that function within the watershed, divided by the total of that ecosystem function within the region (i.e. summed over all watersheds).

Equation 1:

$$\mathrm{EFimportance}_{nw} = \left(\frac{EF_{nw_{T_0}}}{\sum_{1}^{w} EF_{nw_{T_0}}} \right)$$

Where EF is the potential ecosystem function or provision (n) in a watershed (w) in the baseline situation (T_0).

The importance of the watershed for the potential provision of a *group* of ecosystem functions (g) can then be assessed as follows:

Equation 2:

$$\mathrm{EFimportance}_{gw} = \sum_{1}^{n} \left(\left(\frac{EF_{nw_{T_0}}}{\sum_{1}^{w} EF_{nw_{T_0}}} \right) \right)$$

A change in the provision of an ecosystem function was assessed by calculating the relative change with respect to the provision summed over all watersheds (i.e. the region) of that ecosystem function in the baseline situation. Otherwise, the change for a watershed cannot be assessed as the total for the region (r) changes between the baseline and the future situation. Where T_1 is the future situation under a given scenario.

Equation 3:
$$\Delta \text{EFImportance}_{nr} = \sum_{1}^{w}\left(\left(\frac{EF_{nw_{T_1}} - EF_{nw_{T_0}}}{\sum_{1}^{w} EF_{nw_{T_0}}}\right)\right)$$

Similarly, the change in contribution of potential provision for a group of ecosystem functions is assessed as follows:

Equation 4:
$$\Delta \text{EFImportance}_{gw} = \sum_{1}^{n}\left(\left(\frac{EF_{nw_{T_1}} - EF_{nw_{T_0}}}{\sum_{1}^{w} EF_{nw_{T_0}}}\right)\right)$$

Results for decreases in ecosystem function provision were normalised using the same approach as biodiversity importance (see section 2.8), and increases were similarly normalised, albeit from 0 to 1. Decreases were displayed in three classes based on natural breaks for data in the scenario with the highest loss (as with biodiversity loss; see section 3.3). Zero values were displayed as no change, whereas increases were shown as a single positive class. Baseline results were shown in five classes based on natural breaks.

Assumptions and limitations

The definition of cultivated products in this methodology is limited to soft commodities (i.e. crops) and does not include plantation forests. However, since plantation forest is not a specific class in the GLC2000 land cover dataset used for the model initialisation, any existing plantation forest will be classed as forest and can thus be converted to other land uses such as agriculture during modelling. This could for example mean that planted woodlots outside protected areas are lost, which may increase pressure on forests within protected areas to satisfy the need for wood products.

Similar to the biodiversity metric, the ecosystem function metric is area-based and so with more area of a certain land-use type within a watershed, the amount of provision coming from this land use will increase, contributing to the watershed's overall importance. Larger watersheds are therefore likely to be more important in terms of provision. When considering the distribution of importance over a single area, the metric should be applied to equal units, as in a raster.

Furthermore, agricultural yields and livestock densities are not considered in the provision metric, therefore similar-sized areas with different productivity levels would not yield different provisioning values.

2.10 Pressure and threat

Threat to biodiversity from agricultural development

The potential threat to biodiversity from agricultural development under the different scenarios can be assessed by comparing the future commodity provisioning function (which is based on agricultural area) with baseline biodiversity of a watershed. However, since agricultural area may have been substantial in the baseline data, a better measure is the expansion of agricultural area. Therefore, the expansion of agricultural area in each watershed was plotted against the baseline biodiversity for that same watershed. A watershed with a high biodiversity value and a large projected expansion of agriculture is likely to be more threatened.

Pressure and threat using Co$ting Nature

In addition to the scenario-based analysis of potential future threat from agriculture to biodiversity and ecosystem functions, current pressures and future threats in the watersheds were assessed using the Co$ting Nature ecosystem services assessment tool (Mulligan, 2010; 2015) (www.policysupport.org/costingnature). Co$ting Nature uses a range of different datasets (global) to calculate an index of pressures and threats at a high spatial resolution (1-km). For each watershed, the mean value of pressures and threats was calculated and normalised.

Data

In Co$ting Nature, current pressure of human activity is calculated according to the mean normalised values for recent land use change, human population density (based on Landscan data), fire frequency calculated from the MODIS burned area product (Mulligan, 2010), grazing intensity for both wildland and managed grazers (Wint & Robinson, 2007), agricultural intensity for pastures and croplands (Ramankutty, 2008), dams (Mulligan *et al.,* 2011) and infrastructure (upstream dams and local mines, oil and gas, urban areas and roads).

Threats are calculated according to:

- Planned infrastructure,
- Presence of resources,
- Relative accessibility from towns of 50,000 population (Uchida & Nelson, 2009),
- Relative proximity to recently deforested areas (i.e. Deforestation fronts),
- Relative projected change in GDP and population (CIESIN & CIAT, 2005),
- Relative projected change in climatic temperature and precipitation to the 2050s,
- Relative current distribution of night-time light intensity as an indicator of otherwise undefined threats,
- Global maps of mining and oil and gas concessions derived from multiple national and international sources alongside,
- A global map of planned roads derived from multiple sources are used to define areas where infrastructural change is planned or likely.

All of these factors are then normalised and combined into a single metric.

Assumptions and limitations

While species-specific information on threats is available for some species in the IUCN database, these were not related to the specific threats and pressures in the watersheds during the analysis. The main reason for this is that threats to species are usually recorded across species groups, and do not specifying where the threat occurs within the species' range. Therefore, impacts from these threats cannot be determined using this methodology. For example, impacts of extractive activities are context-specific and a function of size and type of activities, but also of associated infrastructure development.

3 Results

3.1 IMPACT commodity trends

In order to understand agricultural land-use change in the Lake Victoria Basin, results on projected production, yield and area expansion from the global agro-economic model IMPACT are discussed. The results are discussed for countries rather than the basin since the IMPACT model provides results at national scales that cannot reliably be disaggregated to sub-national scales.

The production of staple crops, meat increases under all scenarios in order to meet the demands of growing populations. For example, maize, beef and coffee show a sharp increase in production until 2050 (Figure 6). These results include the impacts of climate change. The Industrious Ants scenario (S1) yields the highest production in 2050 for maize and beef in all countries, reflecting the strong focus on promoting staple foods rather than high-value crop exports in this scenario. Increased meat production in the Industrious Ants scenario is largely driven by the strong economic development and wealth increases that lead to a shift in diets. The Herd of Zebra scenario (S2) shows relatively high coffee production up to around 2040 after which production runs parallel with the S1 scenario, which is the result of the strong push for export agriculture in this scenario. For all three commodities, the Sleeping Lions scenario (S4) shows the lowest outputs – this is expected, given this scenario has a negative outlook on economic growth and governance in this scenario with very little investment in agricultural development.

The model does not capture the variability in production over time as shown by data on past trends (based on FAO statistics), but indicates the general expected trend to 2050. With the exception of the Herd of Zebra scenario (S2), beef production is projected to slowly rise until around 2025 and then rapidly increase. The delay in increase of beef production in the S2 scenario is the result of lower demand for meat products until around the early 2020s due to high food prices. The drought in the early 2020s that is part of all scenario narratives can also be seen in the production trends. In particular in the S2 scenario, the rocketing food prices due to the drought kick-start investments in climate-smart food production which rapidly increases production and lowers food prices. Impacts of climate change are also visible in these production trends, e.g. the dip in maize production under all scenarios in Tanzania is the result of projected climate change which particularly impact production around that period (see Figure 8).

Different levels of expected population growth drive projected increases in production between scenarios. The population of Burundi is projected to more than double, reaching nearly 17 million by 2050 (7.2 million in 2005) with much agreement between scenarios. The population of Rwanda is projected to grow to between 20–26 million from just over 9 million in 2005, while Uganda's population shows a large variation between scenarios with projections between 78 million (Industrious Ants) and 113 million (Sleeping Lions) from 28 million in 2005. A similar variation between scenarios is found for Kenya which is projected to reach a population between 72 and 96 million (from 36 million in 2005) and Tanzania with a projected population of between 87 and 121 million by 2050 (39 million in 2005). These population increases have a clear impact on the demand for crop and livestock products. In particular, the demand for meat products cannot be fulfilled by domestic production in four of the five countries (Figure 7). The only exception is Kenya, where lamb and beef production is greater than demand for a number of decades. However, for both lamb and beef, demand is greater by 2050 than national production. In addition to population growth, all scenarios are also affected by the impacts of economic development. This leads to an overall increase in wealth, living standards and aspirations, driving changes in consumption patterns towards more land and resource intensive commodities.

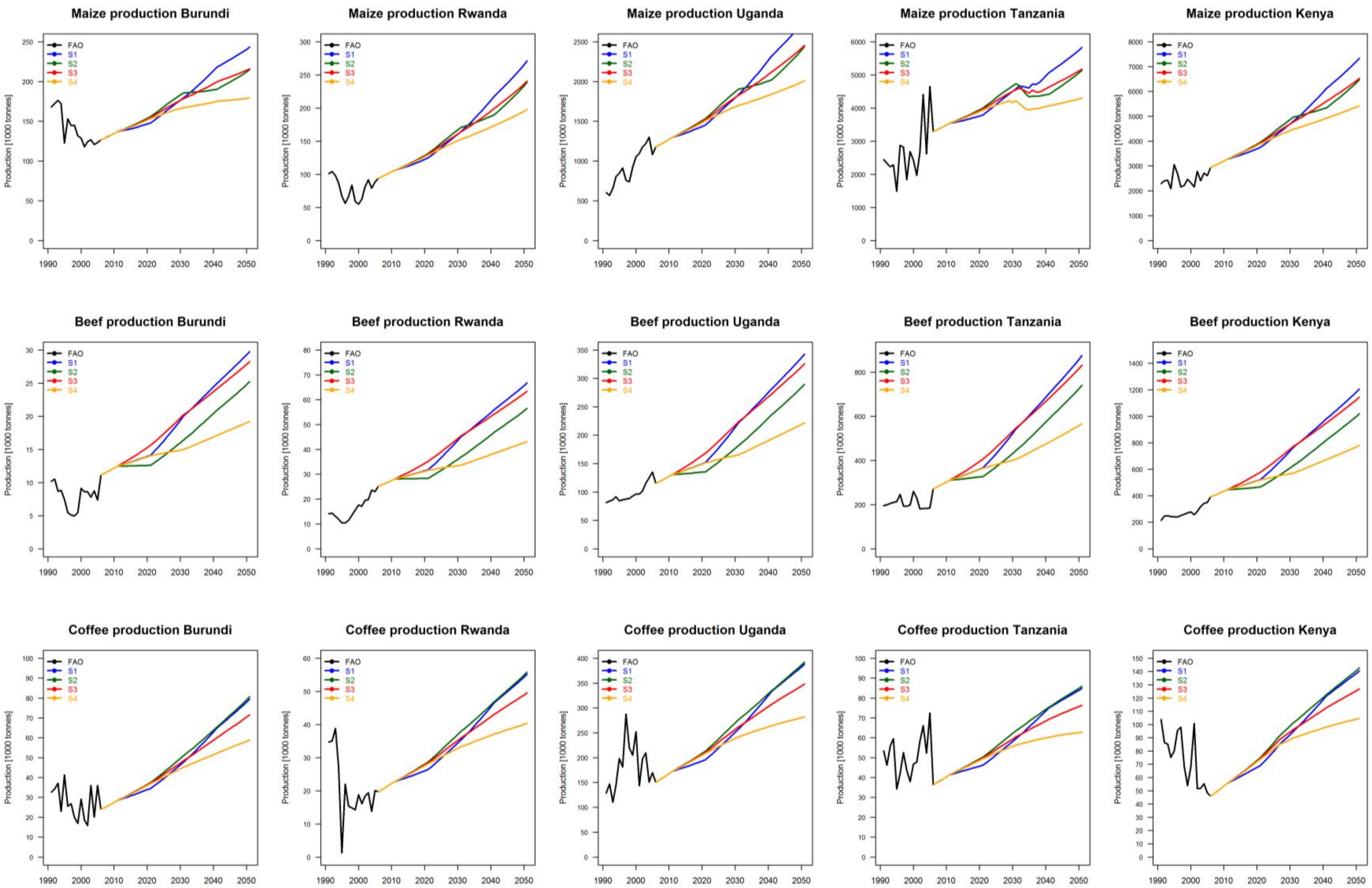

Figure 6: Recent trends (black based on FAO statistics) and future (colours, based on IMPACT model) projections of maize, beef and coffee production under four regional scenarios for the Lake Victoria Basin countries with climate change impact S1: Industrious Ants.

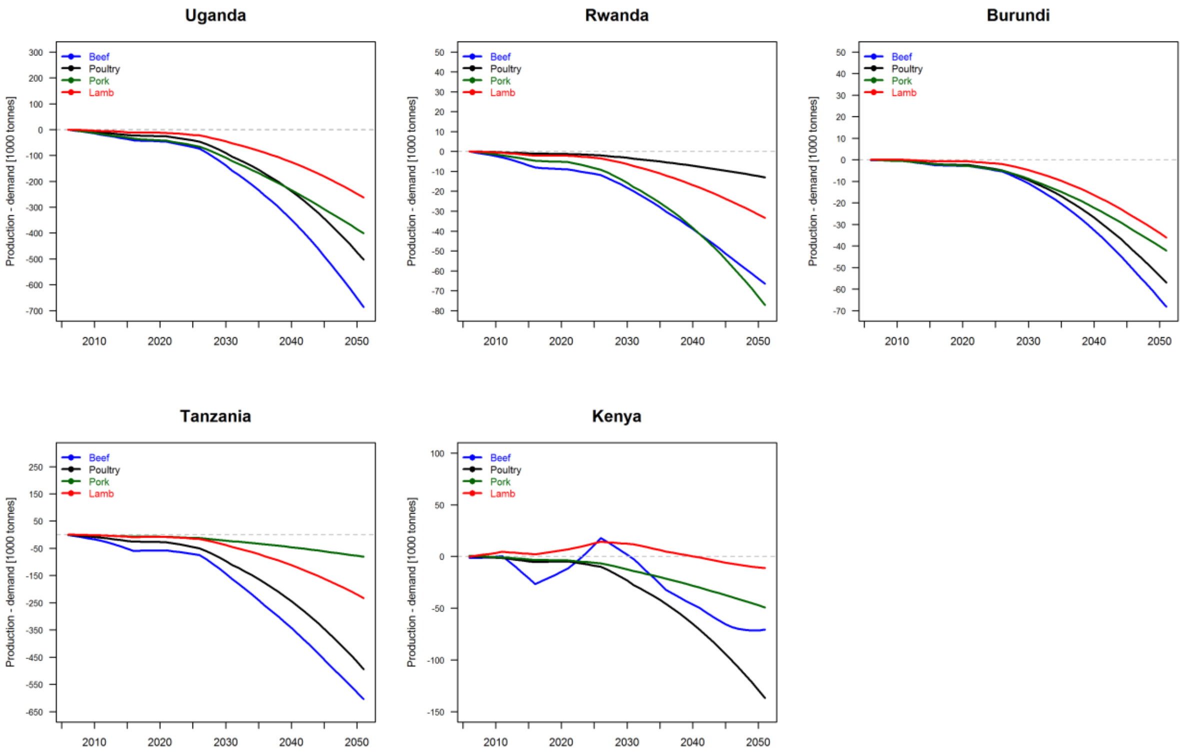

Figure 7: Difference between domestic production and demand for meat products in the Lake Victoria Basin countries between 2005 and 2050 for the Industrious Ants scenario. Blue lines show beef, black show poultry, green show pork and red show lamb.

Projections of yield and production for some key crops in all five countries under the Industrious Ants scenario (S1) with and without climate change, show an increase under climate change as modelled with the IPSL model using the RCP 8.5 emission pathway (with the exception of dry beans in Uganda and Maize in Tanzania) (Figure 8). Increases of up to 27% for dry beans in Rwanda and a mean increase of 11% by 2050 are seen compared to under a no climate change pathway (Figure 8). In most cases the increase in yield leads to an increase in total production output. It should be noted however, that these final yield results also include economic feedbacks. Therefore it is possible that yield gains are the result of a price response from changes (e.g. production reduction due to climate change) in global markets which lead to increased investment and inputs generating higher yields where this is possible, even though climate change may actually have a negative impact on yields. As previously mentioned, the RCP 8.5 scenario assumes the greatest increase in temperature of all RCPs which can have a positive impact on yields. However, precipitation changes are also important and could potentially offset any yield gains through temperature. Different climate change projections based on different emission scenarios are likely to show smaller changes in crop yields (e.g. Wiebe *et al*., 2015).

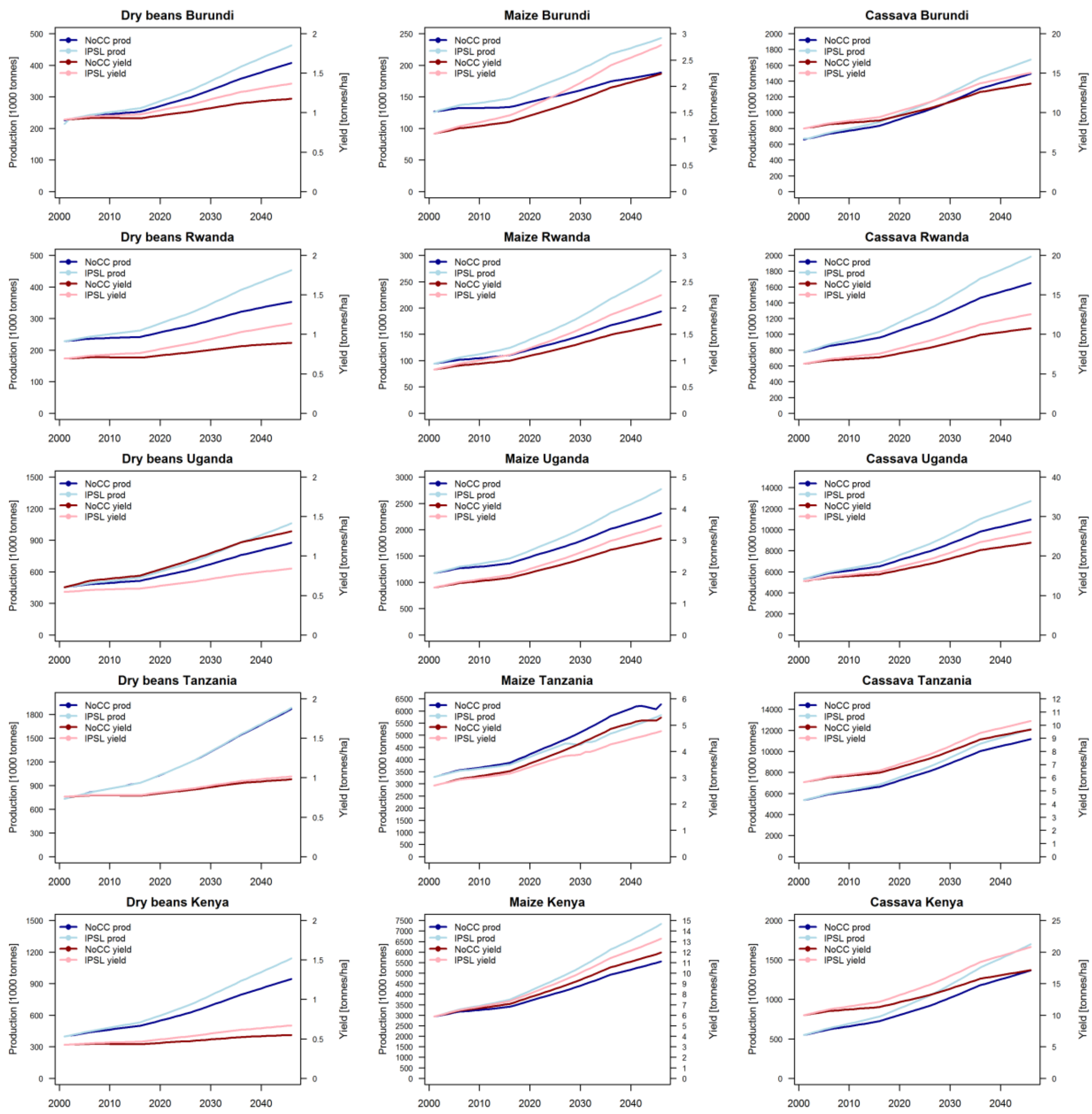

Figure 8: Trends in production and yield for three important crops in the Lake Victoria Basin countries for the Industrious Ants (S1) scenario with no climate change (NoCC) and with climate change based on the IPSL GCM.

Different types of crop show different patterns of area expansion versus yield in order to meet growing demands (Tables 3 and 4). Crop area expansion in the model is largely driven by changes in crop prices, e.g. if prices of one crop go up faster than another, this crop will expand in area. Increases in production for a staple crop like maize, is expected to be largely due to yield increase and not so much from area expansion, whilst on the other hand the increased production of sugarcane and beans (both a staple and cash crop) is expected to come largely from area expansion rather than yield, with potential implications for the area under food crops or natural habitats. Increased production of fresh vegetables is expected to come from both yield and area increases in most countries. The expected tripling in rice paddy area in Kenya is particularly striking (Table 3). Most rice in Kenya is irrigated and located near wetlands (Muhunyu, 2012), and such an increase in area is likely to have impacts on water ecosystem services and biodiversity.

Table 3: Yield, Area and Production changes (%) for seven crops for Burundi, Rwanda, Uganda, Tanzania and Kenya under scenario S1: Industrious Ants, between 2005-2050

	Maize			Cassava			Fresh Vegetables			Rice Paddy			Coffee			Dry beans			Sugarcane		
	Yield	Area	Prod.	Yield	Area	Prod.	Yield	Area	Prod.	Yield	Area	Prod.	Yield	Area	Prod.	Yield	Area	Prod.	Yield	Area	Prod.
Burundi	153	-24	92	88	35	154	144	56	401	49	1	472	136	30	232	50	37	116	10	95	115
Rwanda	170	7	188	100	29	157	202	46	536	108	4	553	134	19	180	65	21	99	38	69	133
Uganda	130	2	136	92	24	138	173	67	356	123	27	202	128	13	158	54	52	135	49	57	134
Tanzania	76	3	78	82	24	126	142	7	158	58	19	113	119	7	134	34	92	157	6	103	115
Kenya	126	-3	150	108	49	209	181	59	375	55	306	532	152	11	205	58	82	187	22	70	124

Table 4: Absolute area changes between 2005-2050 (ha X 1000)

	Maize	Cassava	Fresh Vegetables	Rice Paddy	Coffee	Dry beans	Sugarcane
Burundi	-27.5	28.7	21.3	0.3	8.3	91	2.1
Rwanda	7.6	35.1	32.3	0.5	5.8	68.6	2.1
Uganda	18.6	95.3	105.6	28.8	33.5	434	19.9
Tanzania	75.6	227.2	17.5	125.5	8.5	888.6	20.3
Kenya	-50.7	26.8	86.0	53.7	19.4	766.2	39.1

3.2 Land-use change

Land use change under strict conservation of existing protected areas

In this section, results for land use change under the different scenarios are shown for the strict conservation policy option, meaning that existing protected areas are restricted for conversion to other land uses. The impact of considering alternative conservation policy options (no-conservation or extended protected areas) is discussed in the 'alternative conservation policy options' section below.

Land-use patterns are largely similar under the four scenarios (Figure 9). Areas of natural land cover such as forests and grass/shrubland decline whilst crop, pasture and urban areas expand (Figure 10). The consistency among scenarios is due to the fact that increases in demand for agricultural products are mainly driven by strong increases in population under all scenarios, and therefore lead to similar land use change patterns. These patterns are also driven by the agricultural suitability of land, which is strongly driven by climate (see section 3.1).

Urban growth occurs in each country under all scenarios. The largest urban expansion can be seen in the Kenyan part of the basin, around Kampala and Entebbe in Uganda and scattered throughout Rwanda and Burundi (Figure 9). Increase in urban extent is slightly higher under the Sleeping Lions scenario than under the other scenarios (S4; Figure 10). Urbanisation in combination with increased wealth leads to higher consumption of meat (Figure 6) and fresh vegetables (Table 3), leading to changes in land use beyond those to meet increased demands for staples by a growing population.

The expansion of cropland area is driven by different commodities for different countries. In Burundi, nearly 50% of expansion of cropland area comes from the production of sweet bananas, whereas in Uganda and Rwanda this expansion can mostly be attributed to plantain and sorghum production, while in Kenya and Tanzania the greatest absolute cropland expansion can be attributed to production of dry beans (Tables 3 and 4).

Expansion of agriculture primarily results in loss of grassland/shrubland, which is nearly double that of forest loss. The majority of deforestation in the region occurs in the Kenyan part of the basin. In Rwanda and Burundi there is much deforestation but in particular conversion of large areas of grassland/shrubland to croplands under all scenarios.

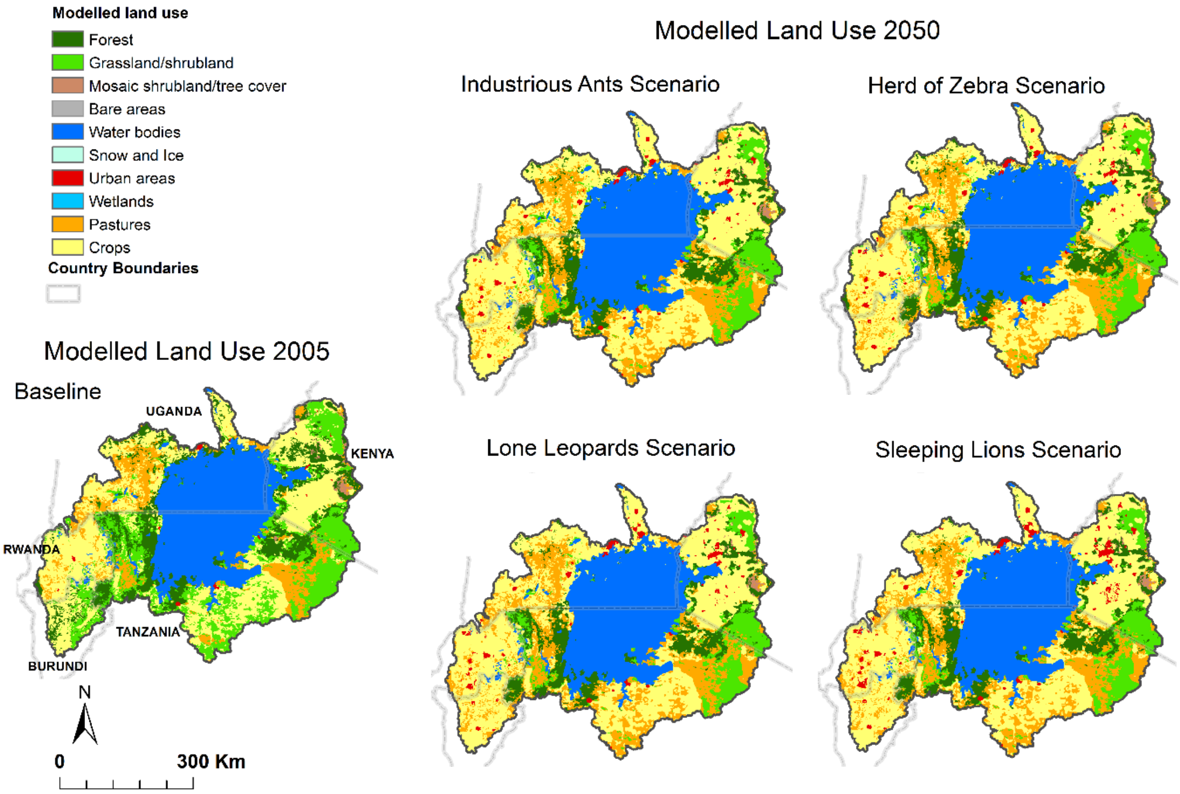

Figure 9: Land use: Maps of baseline (2005) and potential future (2050) land use in Lake Victoria Basin for a strict conservation policy option.

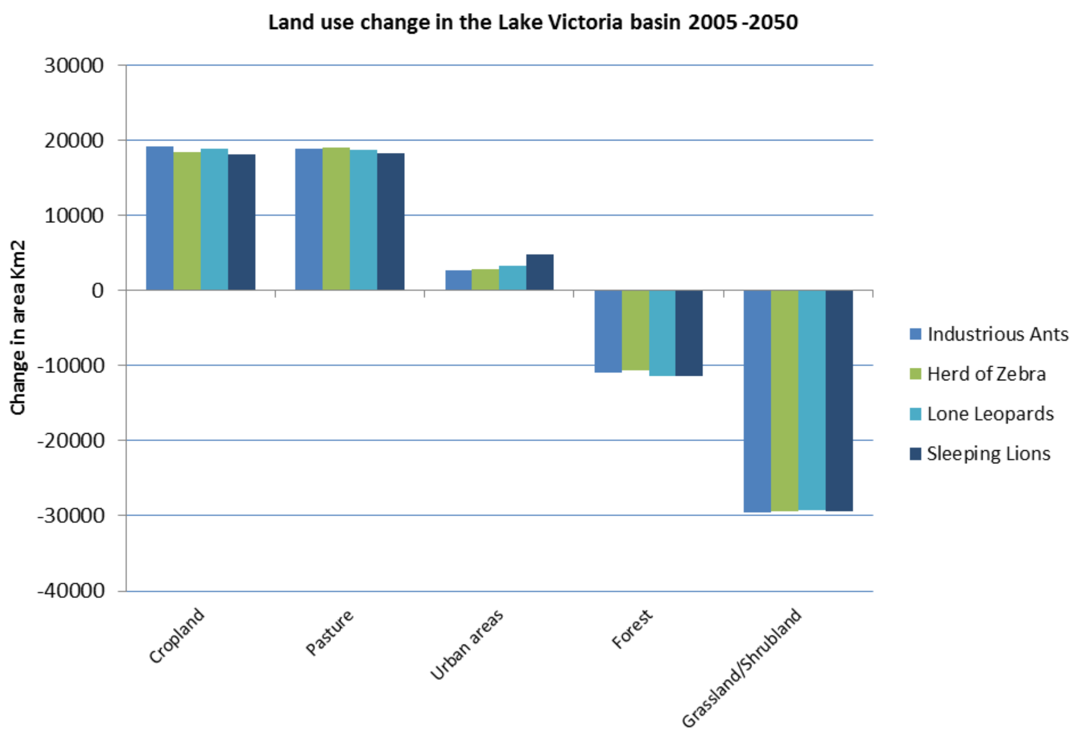

Figure 10: Land-use change: potential change in area (km^2) for major land-use categories between 2005 and 2050 within the Lake Victoria basin.

Alternative conservation policy options and forests

Broadly, land use patterns within the basin under the alternative conservation policy options are very similar to those under the strict conservation policy option described in the previous section (see Figure 11 and 12 for no-conservation alternative and extended conservation alternative respectively) which is partly due to the relatively low number of protected areas within the basin (see Appendix VI for location of Protected Areas and Key Biodiversity Areas) as well as more suitable lands available elsewhere in the country to satisfy the demand for land.

The effects of the different conservation policy options become clearer when focussing on a single land use that is important for biodiversity and ecosystem functions and strongly affected by agricultural expansion in the lake Victoria Basin: around 28% of forest is projected to be lost within the area of the five countries covered by the Lake Victoria Basin compared to about 8% outside of the basin boundaries. However, restricting the conversion of natural land to cropland or grazing land as under the extended conservation alternative (i.e. turning Key Biodiversity Areas into protected areas) leads to more overall forest loss within the five basin countries (Figure 13). Forest loss within the basin shows the same pattern (Figure 14): slightly more forest is lost under an extended conservation alternative with almost no difference between the no-conservation alternative and strict conservation policy. Most forest is found outside protected areas and Key Biodiversity Areas, and therefore conversion of this land leads to more forest loss overall. In this case, the level of protection in protected areas or Key Biodiversity Areas does not much affect overall forest conservation (Table 5), though other important habitats within these areas may be. These results show that expanding conservation areas can lead to displacement of land use and impact biodiversity and ecosystem functions elsewhere (see also 3.3). It also shows the importance of using spatially explicit approaches to considering potential trade-offs and linkages among land uses and considering large geographical units such as countries or large basins.

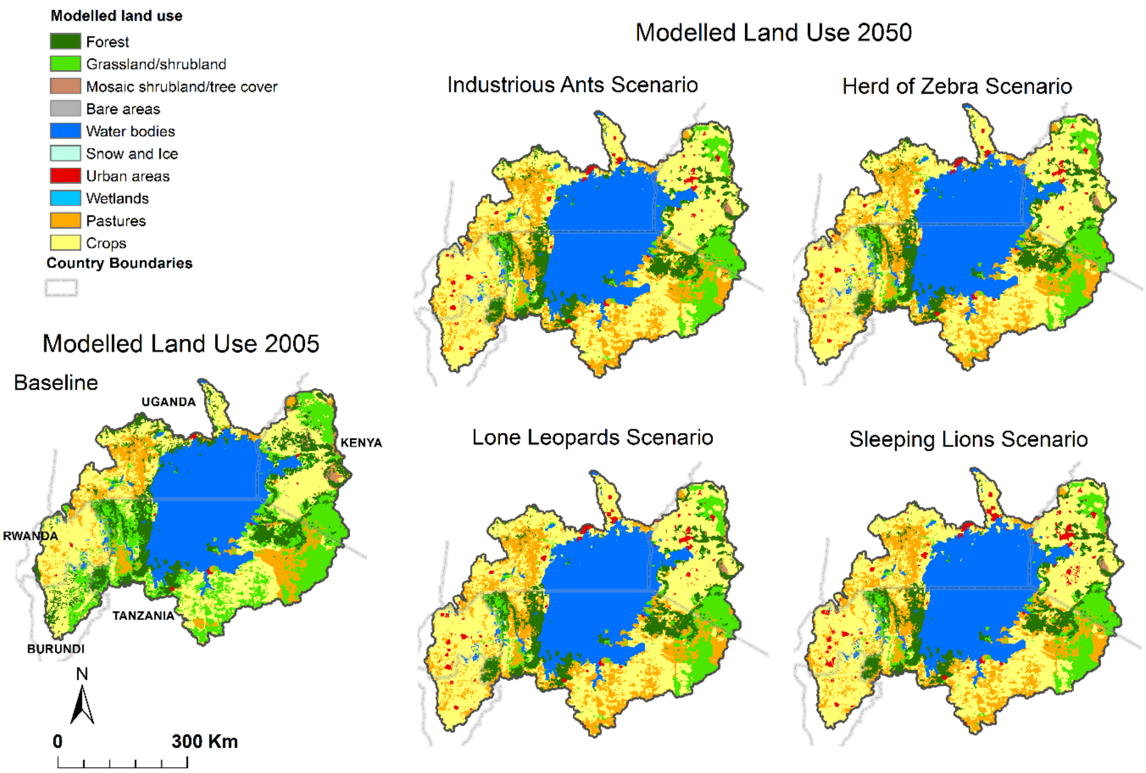

Figure 11: Land use: Maps of baseline (2005) and potential future (2050) land use in Lake Victoria Basin for a no-conservation policy alternative.

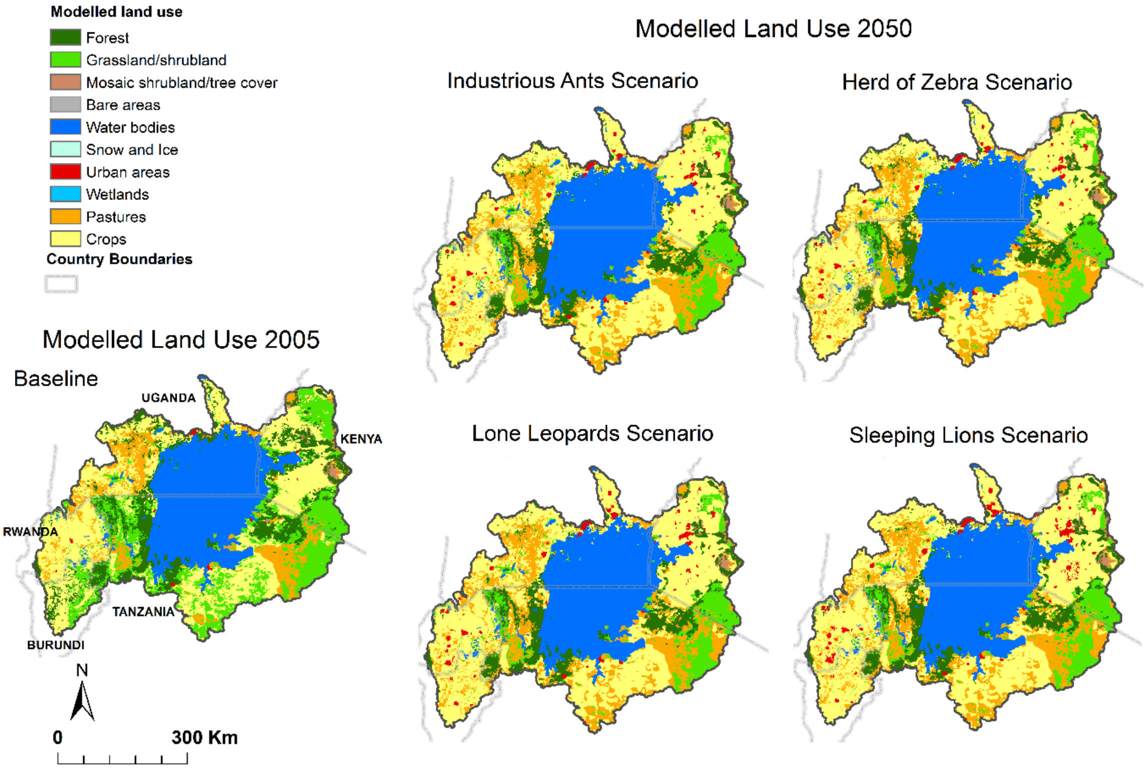

Figure 12: Land use: Maps of baseline (2005) and potential future (2050) land use in Lake Victoria Basin for an extended conservation policy alternative.

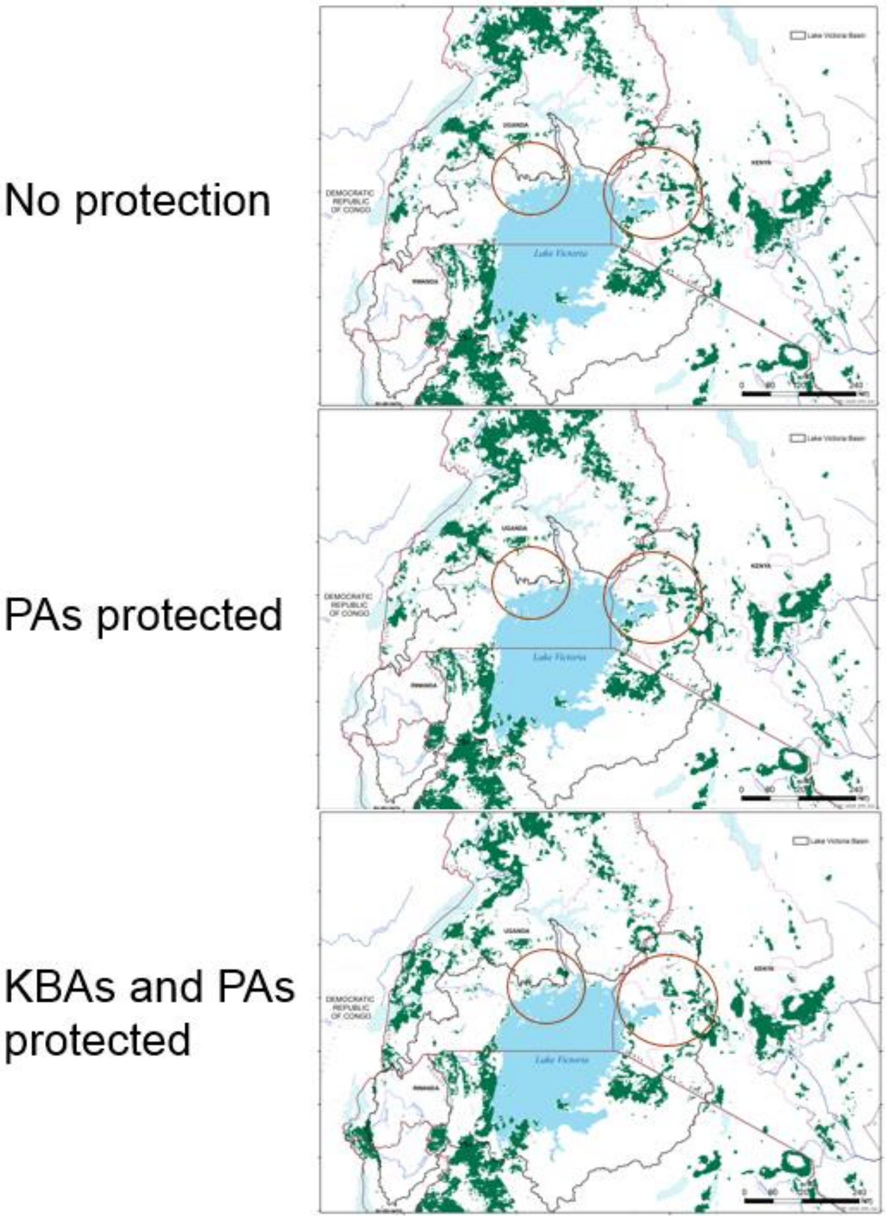

Figure 13: Land use change. Extent of forest under different conservation policy options. Red circles highlight differences in forest loss within the basin.

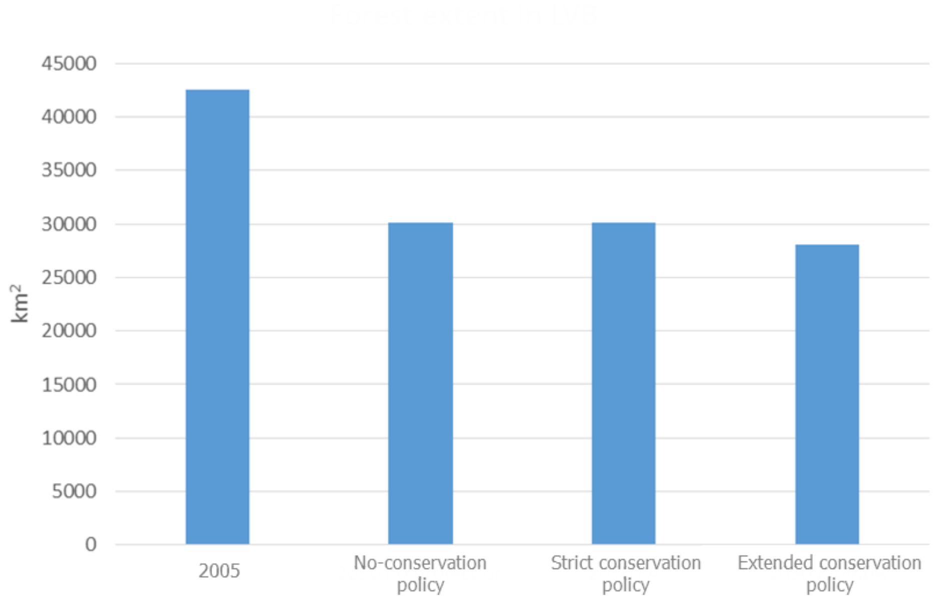

Figure 14: Modelled forest extent in the Lake Victoria Basin in 2005 and 2050 under three different conservation policies.

Table 5: Extent of forest in protected areas and Key Biodiversity Areas in the Lake Victoria Basin and for all five countries for 2005 and 2050 in km^2 for the Herd of Zebra scenario (S2) under different conservation policy options.

	Lake Victoria Basin				Five Countries			
Date	2005	2050			2005	2050		
Conservation policy option		Strict	None	Extended		Strict	None	Extended
Protected areas	9,434	9,278	7,636	9,288	152,652	152,113	145,423	152,209
Key Biodiversity Areas	7,403	6,664	5,890	7,343	149,094	142,217	138,524	148,468
All region	42,569	30,477	30,431	28,721	529,648	485,003	486,412	484,092

3.3 Biodiversity impacts

Results of the biodiversity impact assessment for all scenarios and conservation policy options are discussed. However, only aggregated results for all species are discussed – the biodiversity results incorporate amphibians, birds and mammals.

When interpreting the results it should be noted that the biodiversity metric is based on absolute areas. Therefore, a higher score is likely when there was a high proportion of suitable habitat in a watershed relative to the region. In addition, higher scores for biodiversity could be the result of a diversity of land-cover/land-use types, or a high number of endemic or restricted range species.

In the strict conservation policy option, watersheds with high baseline biodiversity importance are also where the potential losses are highest for all four scenarios (Figure 15). Impacts on biodiversity are spatially consistent across all scenarios - the only difference was the intensity of impacts for a number of watersheds. This shows that population and climate change ultimately drive impacts on biodiversity that override the effect of governance, regional integration or other more uncertain institutional or political factors.

The results for the no-conservation (Figure 16) and extended conservation (Figure 17) policy options are very similar, with a number of watersheds showing increased loss under a no-conservation policy alternative – these are predominantly located on the Kenyan side of the basin. However, other watersheds showed the reverse and experienced higher biodiversity loss under an extended conservation policy alternative. The latter results are a good example of spatial trade-offs in impacts (see also section 3.2. on displacement of forest loss). Due to stricter conservation policies elsewhere, natural land has been converted in these less well protected watersheds, affecting overall biodiversity more than without these policies in place.

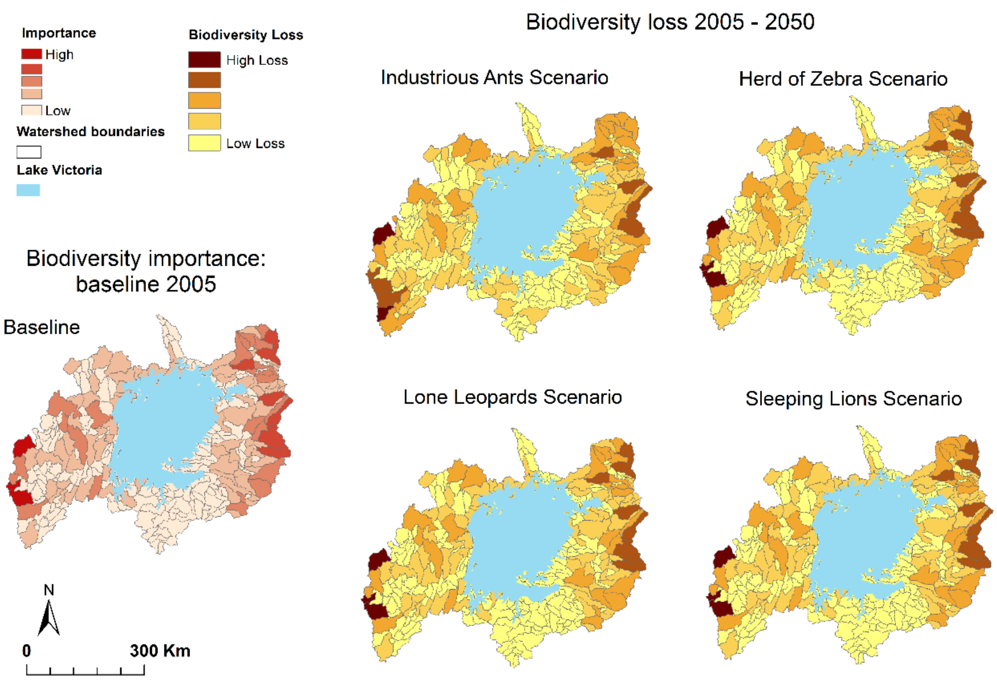

Figure 15: Baseline biodiversity importance and projected changes in biodiversity importance between 2005 and 2050 for watersheds in the Lake Victoria Basin under a 'strict conservation' policy option.

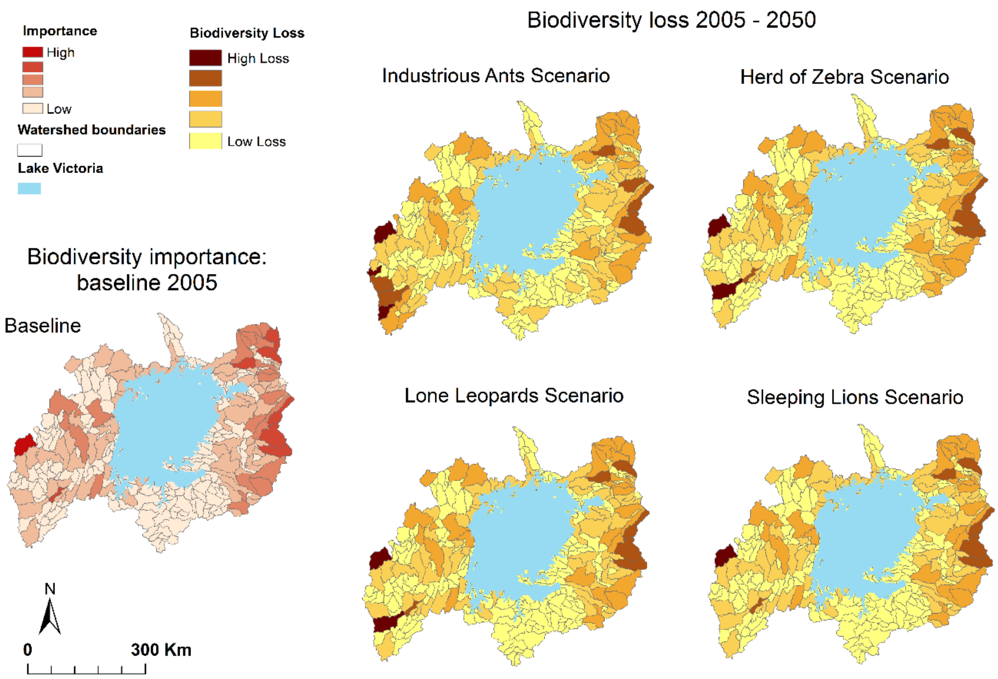

Figure 16: Baseline biodiversity importance and projected changes in biodiversity importance between 2005 and 2050 for watersheds in the Lake Victoria Basin under a 'no-conservation' policy option.

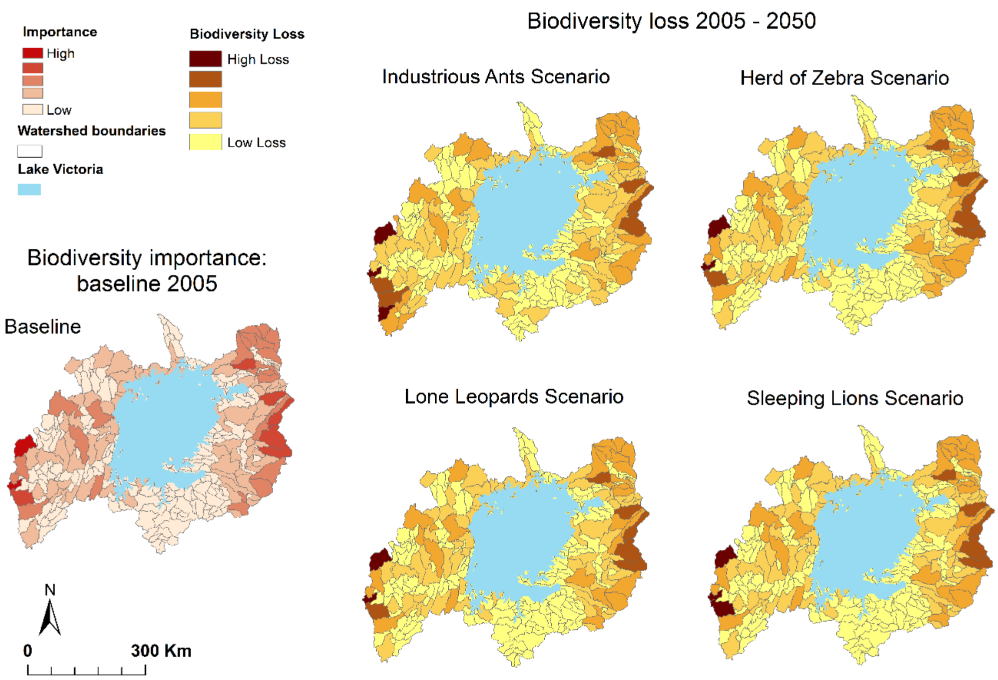

Figure 17: Baseline biodiversity importance and projected changes in biodiversity importance between 2005 and 2050 for watersheds in the Lake Victoria Basin under an 'extended conservation' policy option.

3.4 Ecosystem function impacts

There are large variations in ecosystem function provision among the watersheds of the Lake Victoria Basin (Figures 18-20). Commodity provision tends to be high in areas with cropland and pastureland whereas regulating and wild provision are particularly high in areas with a lot of forest. Since ecosystem function provision in a watershed is a function of the total area of different land uses, larger watersheds are likely to have greater total provision. Under a strict conservation policy option, most watersheds show an increase in commodity provision between 2005 and 2050 as a result of the increased agricultural land use.

Increases in commodity provisioning functions (Figure 18) often trade-off with regulating and wild provision functions (Figure 19-20) through the loss of natural land, though some areas lose both commodity and regulating functions under all four scenarios, such as the eastern part of the basin, north and south of the Winam gulf in Kenya. This is the result of the increasing urban footprint which reduces land available for any ecosystem function provision. Decreases in regulating functions are seen particularly on the western part of the basin in Uganda, Rwanda and Burundi (Figures 18-20) mostly through forest loss.

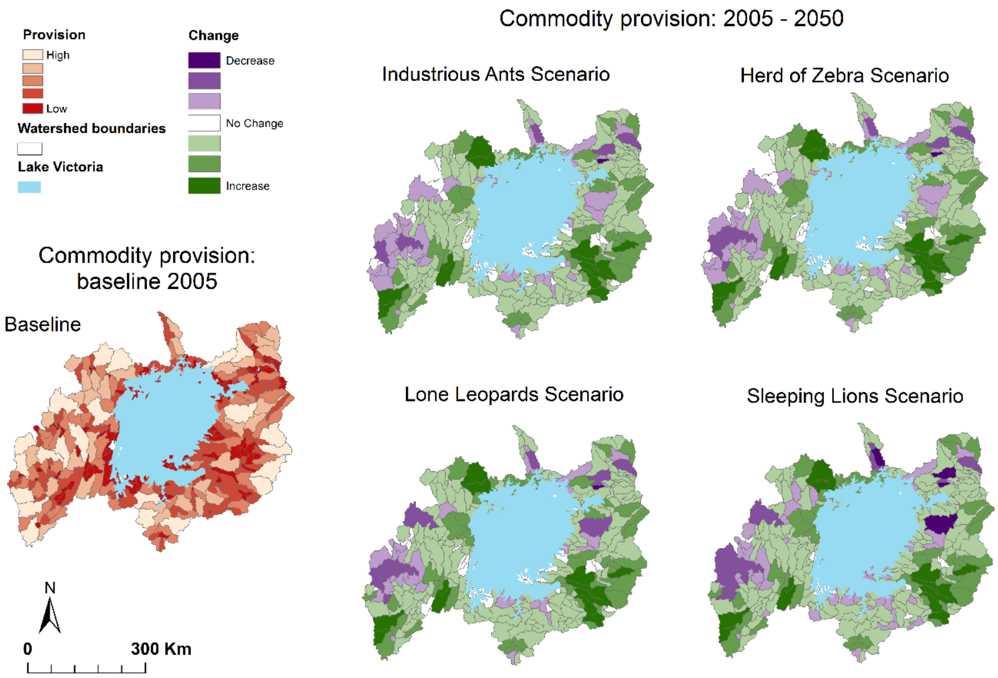

Figure 18: Commodity Provision: Baseline provision and projected changes between 2005 and 2050 for watersheds in Lake Victoria Basin under a 'strict conservation' policy option.

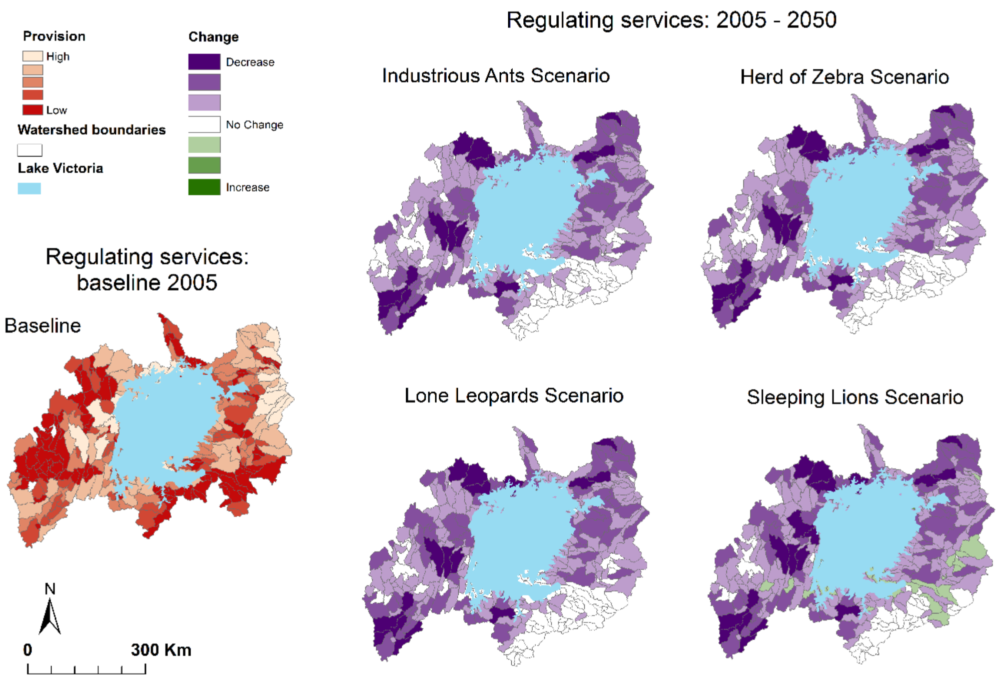

Figure 19: Regulating Services Provision: Baseline provision and projected changes between 2005 and 2050 for watersheds in Lake Victoria Basin under a 'strict conservation' policy option.

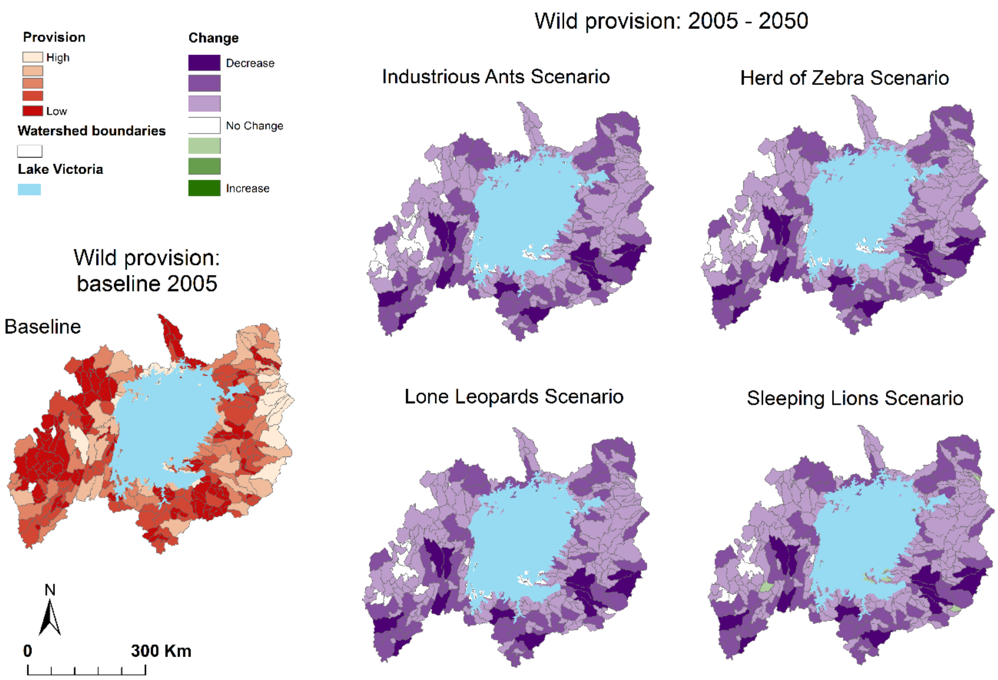

Figure 20: Wild Provision: Baseline provision and projected changes between 2005 and 2050 for watersheds in Lake Victoria Basin under a 'strict conservation' policy option.

Ecosystem functioning impacts for conservation policy options are aggregated among all ecosystem functions (commodity provisioning, regulating and wild provision) in Figures 21 and 22. Losses of ecosystem functioning are greater under the no-conservation policy alternative for a large number of watersheds in all countries in the basin (Figure 21), while losses are lowest under the extended conservation option (Figure 22), reflecting the importance of non-forest natural land uses in providing regulating and wild provisioning. Even though relatively more forest is lost under the extended conservation option (see section 3.2), the restrictions on conversion of land leave other natural land uses intact to deliver regulating and wild provisioning services whilst commodity provisioning services are more limited under this policy option. Ultimately the changes in total ecosystem function provisioning depend on the balance between the increased commodity provision through conversion to agricultural use at the expense of regulating and wild provision land uses, as shown above (Figures 18-20).

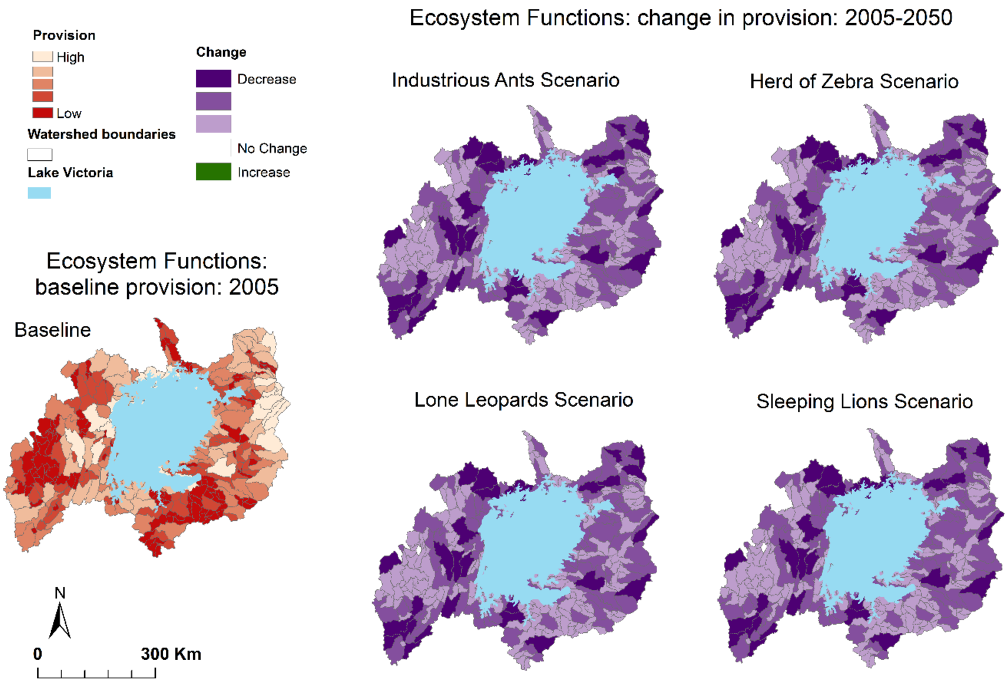

Figure 21: Ecosystem Function Provision: Baseline provision and projected changes between 2005 and 2050 for watersheds in Lake Victoria Basin under a 'no conservation' policy option.

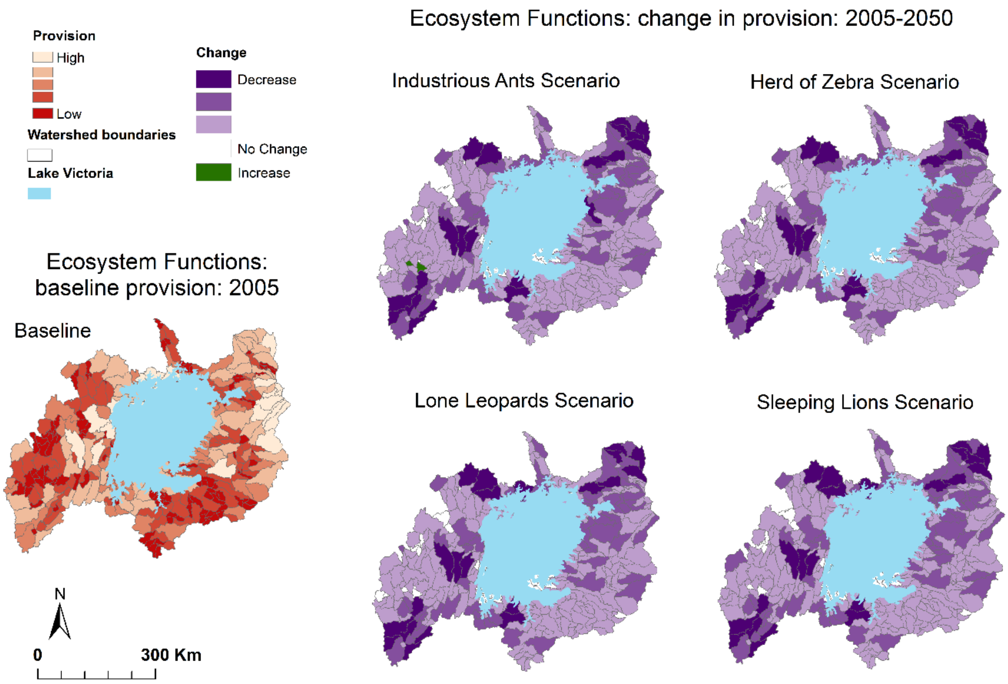

Figure 22: Ecosystem Function Provision: Baseline provision and projected changes between 2005 and 2050 for watersheds in Lake Victoria Basin under an 'extended conservation' policy option.

3.5 Pressure and threats

Threat to biodiversity from agricultural development

The normalised scores of projected agricultural expansion and baseline biodiversity show three watersheds highlighted as particularly under threat (Figure 23). These watersheds all have relatively high biodiversity values and are projected to undergo significant conversion of land to agricultural use under at least three of the four scenarios and are thus most under threat in the basin Therefore, these three watersheds have high suitability for agricultural expansion, however their high biodiversity importance values should be taken into special consideration in land use planning.

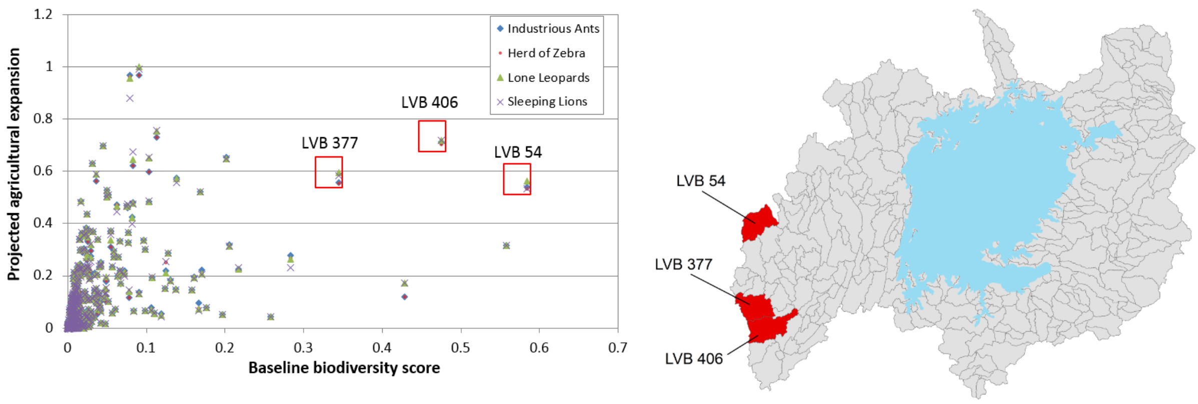

Figure 23: Projected agricultural expansion and baseline biodiversity (0-1) for Lake Victoria Basin under a 'strict conservation' policy option.

Pressure and threat using Co$ting Nature

The current and future pressure index based on Co$ting Nature data are shown in Figure 24. Highest values for current pressures are found in Burundi and in the Tanzanian part of the basin. Future threats increase throughout the basin, particularly for those watersheds adjacent to Lake Victoria.

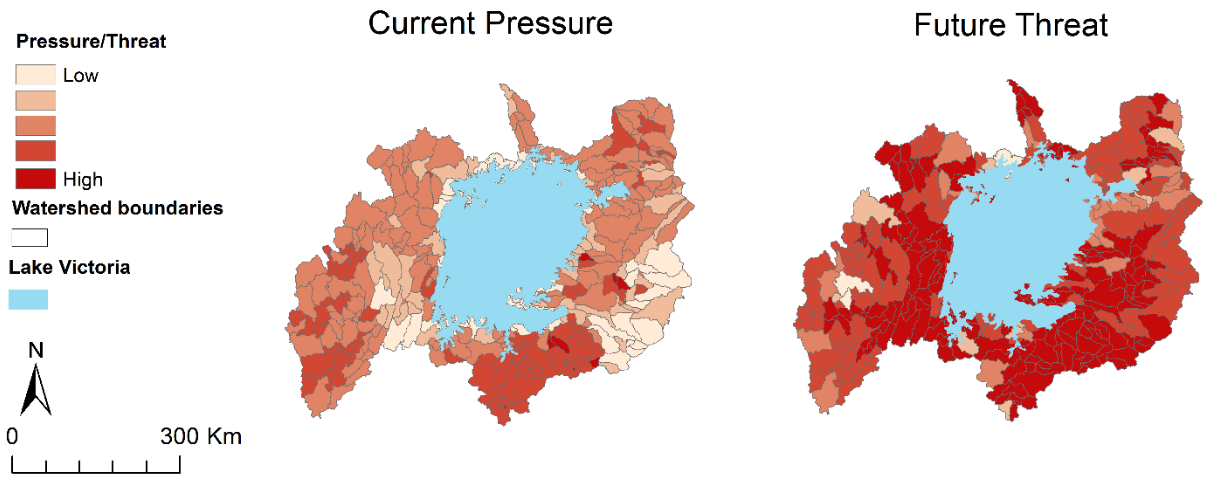

Figure 24: Current pressure and future threat index for Lake Victoria Basin (based on Co$ting Nature data).

4 Conclusions

4.1 Key findings for the Lake Victoria Basin

Crop production in the five countries that encompass the Lake Victoria Basin is projected to increase consistently across all scenarios in the period up to 2050 with production of some crops more than doubling for most countries, both for staple crops and crops associated with increased wealth (both locally and globally), such as fresh vegetables and coffee. Variations in results among scenarios reflect the different governance and agricultural (investment) policy contexts the scenarios create. For example, pro-active governance and regional integration lead to a focus on staple crops to feed the national and regional population, whilst reactive governance favours high value export crops, and leaves a country vulnerable to volatile world market prices. Projected production increases are due to both expected yield increases and area expansion. The results show that yield increases play an important role in projected increases in production for many important food crops, such as maize, but for others, increase in production is expected to come largely from area expansion rather than yield (e.g. sugar cane), with potential implications for areas under food crops or natural habitats. The largest expansion of agricultural land consists of pastures, driven by a strong increase in demand for meat. The Lake Victoria Basin countries will not be able to meet domestic demand for meat by 2050, which will potentially lead to increased imports, which in turn may affect land use elsewhere.

Different production systems require different amounts of land and resources (e.g. for meat, pasture-based versus zero-grazing). Intensification of agriculture, though it may potentially spare land for conservation, can lead to other negative consequences for the environment such as pollution or unsustainable groundwater extraction and should therefore be carefully managed. Social impacts in terms of access to and control over land and resources under any agricultural development strategy should also be considered. Different drivers at various levels (e.g. prices, land availability, market access etc.) support either intensifying production on existing land or area expansion. Depending on the specific question or policy under consideration, this can be investigated in more detail and strategies can be developed to address these drivers.

Impacts of climate change on crop yields (direct and through price effects) plays a key role in determining the amount of land that needs to be converted for agriculture. As the RCP 8.5 scenario is the most extreme scenario of the set of RCP scenarios, the use of different climate projection scenarios would likely cause smaller yield increases or decreases, with different outcomes for land-use change. Non-modelled impacts such as changes in seasonality might also negatively impact yields. Lower yield increases than those projected or decreases in yield, are particular threats to this region – as large amounts of grass/shrubland and forest are projected to be lost for agricultural uses. However, more land would be required if yields remain the same. Negative yield changes due to the impacts of climate change would need to be offset by investment in agriculture, either through technological changes or greater agronomic inputs. The latter may have other unintended negative consequences for the environment, e.g. through increased water pollution. Increased investment in and promotion of climate smart agriculture can help mitigate some of the expected negative impacts of climate change (Lipper *et al.*, 2014).

Deforestation is an important threat to biodiversity and ecosystem functions in the Lake Victoria Basin, particularly given the high biodiversity value of this region where many critical forest habitats are unprotected. Yet, the results show that further expansion of protection to other areas with high biodiversity values does not necessarily lead to less forest loss overall in the future. Moreover, restrictions on conversion of natural land to cropland or grazing land such as the implementation of more protected areas (i.e. including Key Biodiversity Areas) leads to slightly higher rates of forest loss in the Lake Victoria Basin, as most forest suitable for agriculture is located outside these areas. Due to the restrictions, conversion is displaced from non-forested protected areas or Key Biodiversity Areas to non-protected forest areas. Therefore, the role of protected areas and Key Biodiversity Areas should be carefully assessed in a regional context when considering future policy options intended to secure the protection of biodiversity and ecosystem services. Increasing protection in one area may lead to loss of unprotected critical habitat elsewhere.

Different scenarios lead to consistent changes in land use and thus impacts on biodiversity and ecosystem function provision. Even though the scenario narratives differ, projected changes in demand for (particularly food) crops are relatively similar due to the strong overriding influence of population change, urbanisation, increased demand for animal products and climate change. This finding highlights the importance of developing effective actions to mitigate the impacts of a rising population, climate change and growing demand for land and resource intensive commodities locally and globally. The results reinforce the urgency of the need to boost agricultural production by increasing yields whilst putting in place appropriate incentives and regulation to avoid expansion into forest or grass/shrubland areas that hold important biodiversity, and to avoid environmental pollution. This requires – amongst others – significant national-level investment in (climate smart) agriculture, infrastructure, education and family planning, and regional and global efforts on equitable trade agreements.

4.2 Application of scenarios and spatial results

The results show that it is both important and possible to identify spatial patterns of likely threat and pressure that are consistent under different socio-economic futures, as this can help focus action to achieve intended policy outcomes. The analysis of broad patterns under different potential futures, where they are consistent or differ, can support the development of robust policy.

The analysis considered four different plausible socio-economic scenarios for the region, which did not explicitly include a "business as usual" scenario. All scenarios have elements that are consistent with the current situation in various countries. In this study, scenarios were not used to explore alternative future pathways in order to compare them and select a preferred trajectory, but – under the assumption that the future is inherently unpredictable - to support the consideration of future uncertainty in (agricultural) policy development that affects biodiversity and ecosystem services.

The analysis at watershed scale is a useful approach to visualise potential future large scale regional trends, particularly considering the uncertainties introduced in each component of the modelling approach. The visualisation of results in natural biophysical units such as watersheds can inform national or regional level policy-making, which seeks to balance different future demands on land at the national level, or for initial targeting of conservation investments. The land use change assessment was carried out at high (1-km) resolution and results could be aggregated to other units of analysis such as watersheds or used at the underlying 1-km resolution. It is important to note that this analysis, at any level of spatial aggregation, generates and illustrates broad patterns and highlights areas of concern, taking into account the various uncertainties propagated through the modelling framework. Any decision-making process that uses these results should also make sure that local variations not captured in this analysis are integrated and taken into account.

Spatially explicit information and analyses on the effects of different potential trajectories of human-induced landscape change on biodiversity and ecosystem services are crucial to help decision makers balance competing demands on land and to develop more robust and "future proof" policies. It is therefore urgent to increase the access and capacity of all stakeholders to interpret and use such information, and to have an understanding of the data and methods underlying the information.

An important component of this project was supporting the development of such capacity. The methods and results of the spatial analyses were presented, discussed and complemented with expert knowledge during multi-stakeholder workshops involving participants from all five countries within the Lake Victoria Basin: Burundi, Kenya, Rwanda, Tanzania and Uganda. The results were used to review selected national agricultural policies and develop recommendations to make them more robust and adaptable to achieve their intended outcomes under unpredictable future circumstances, and to support regional harmonisation. National follow-up workshops to incorporate recommendations into policies were held in Tanzania, Uganda and Kenya. Finally, to disseminate the approach to a wider audience, an open information and training workshop on using scenarios to consider biodiversity and ecosystem services in plans and policies for agricultural development was held at the African Great Lakes Conference in 2017.

Based on the project experience, a guidance document was developed to accompany this report, setting out how socio-economic scenarios and mapping of their implications for biodiversity and ecosystem services can be used to support the development of more robust policies, and ultimately in making more informed choices which balance conservation and development agendas.

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Appendices

Appendix I: Regional scenario narrative summaries.

East Africa CCAFS scenario narratives

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, 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. However, in the intervening time, 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 appears 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, some key issues are ignored while others overlap or have competing initiatives. The inability of governments to overcome regional disputes and work with together 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 advantageous.

S4: Sleeping Lions - regional fragmentation and reactive governance. This scenario is based on 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 materialise. 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 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

Appendix II: Commodities modelled in the IMPACT model.

IMPACT commodities	
Bananas	Palm Oil
Barley	Pork
Beans	Potatoes
Beef	Poultry
Coffee	Rice
Cassava	Rapeseed Meal
Chickpeas	Rapeseed Oil
Cocoa	Rapeseed
Cotton	Soybean Meal
Cowpeas	Soybean Oil
Eggs	Sunflower Meal
Groundnut Meal	Sunflower Oil
Groundnut Oil	Sunflower
Groundnut	Sorghum
Sheep-Lamb-Goat meat	Soybeans
Lentils	(Sub)-Tropical Fruits
Maize	Sugar Beets
Dairy	Sugarcane
Millet	Sugar
Other Cereals	Sweet Potatoes
Other Pulses	Tea
Other Roots & Tubers	Temperate Fruits
Other crops	Total Other Oilseeds
Pigeon Peas	Total Other Oil meals
Palm Kernel Meal	Total Other Oils
Palm Kernel Oil	Vegetables
Palm Kernel	Wheat
Plantains	Yams

Appendix III: Binary links between landscape characteristics and ecosystem function provision.

	LandSHIFT codes	Commodity Provision	Wild Provision		Regulating			
		Cultivated Products	Wildlife Products	Water Provision	Climate Regulation	Natural Hazard Reduction	Water Regulation	Erosion Prevention
Landscape Characteristics								
Steep Slopes		0	1	0	1	0	0	0
Cloud forests		0	1	1	1	1	1	1
Land Properties/Use								
Forest	1,2,3,4,5,6	0	1	0	1	1	1	1
Tree Cover, regularly flooded, fresh water	7	0	1	1	1	1	1	1
Tree Cover, regularly flooded, saline water	8	0	1	0	1	1	1	1
Mosaic: Tree Cover / Other natural vegetation	9	1	1	0	1	1	1	1
Tree Cover, burnt	10*	-	-	-	-	-	-	-
Shrub Cover, closed-open, evergreen	11	1	1	0	1	1	0	1
Shrub Cover, closed-open, deciduous	12	1	1	0	1	1	0	1
Herbaceous Cover, closed-open	13	1	1	0	0	0	0	0
Sparse herbaceous or sparse shrub cover	14	0	1	0	0	0	0	0
Regularly flooded shrub and/or herbaceous cover	15	1	1	1	1	1	1	1
Cultivated and managed areas	16	1	0	0	0	0	0	0
Mosaic: Cropland / Tree Cover / Other natural vegetation	17	1	1	0	0	0	0	0
Mosaic: Cropland / Shrub and/or grass cover	18	1	1	0	0	0	0	0
Bare Areas	19	0	0	0	0	0	0	0
Water Bodies	20	1	1	1	0	1	1	1
Snow and ice	21	0	0	1	1	1	1	1
Artificial surfaces and associated areas	22	0	0	0	0	0	0	0
Irrigated Agriculture	23	1	0	0	0	0	0	0
Set-a-side	99	0	1	0	0	0	0	0
Cropland	100-120	1	0	0	0	0	0	0
Pasture/grazing land	200-201	1	0	0	0	0	0	0

*Unlikely to occur in areas. Temporary class with no way to determine recovery. Cannot determine future provision

Appendix IV: Crosswalk between IUCN Habitats and LandSHIFT Land-Use Types.

Adapted from crosswalk by Foden *et al.* (2013) who linked IUCN Habitats (IUCN, 2014) to the Land Cover Classification System (LCCS).

		LandSHIFT Land-Use types																										
		Description	Artificial surfaces and associated areas	Bare Areas	Cultivated and managed areas	Herbaceous Cover, closed-open	Irrigated Agriculture	LandSHIFT code - representing cropland (100 to 120)	LandSHIFT code - representing pasture and rangeland (200 and 201)	LandSHIFT code - set-aside	Mosaic: Cropland / Shrub and/or grass cover	Mosaic: Cropland / Tree Cover / Other natural vegetation	Mosaic: Tree Cover / Other natural vegetation	Not applicable	Regularly flooded shrub and/or herbaceous cover	Shrub Cover, closed-open, deciduous	Shrub Cover, closed-open, evergreen	Sparse herbaceous or sparse shrub cover	Tree Cover, broadleaved, deciduous, closed	Tree Cover, broadleaved, deciduous, open	Tree Cover, broadleaved, evergreen	Tree Cover, burnt	Tree Cover, mixed leaf type	Tree Cover, needle-leaved, deciduous	Tree Cover, needle-leaved, evergreen	Tree Cover, regularly flooded, fresh water	Tree Cover, regularly flooded, saline water	Water Bodies
		Code	22	19	16	13	23	**100 - 120**	**200 - 201**	**99**	18	17	9	**999**	15	12	11	14	2	3	1	10	6	5	4	7	8	20
IUCN Habitat Classification																												
Description	**Code**																											
Artificial/Aquatic	15				1		1							1														1
Artificial/Aquatic - Aquaculture Ponds	15.3				1																							1
Artificial/Aquatic - Canals and Drainage Channels, Ditches	15.9				1																							
Artificial/Aquatic - Excavations (open)	15.5				1																							
Artificial/Aquatic - Irrigated Land (includes irrigation channels)	15.7				1		1																					

Artificial/Aquatic - Karst and Other Subterranean Hydrological Systems (human-made)	15.10													1														
Artificial/Aquatic - Ponds (below 8ha)	15.2				1																							
Artificial/Aquatic - Salt Exploitation Sites	15.4				1																							
Artificial/Aquatic - Seasonally Flooded Agricultural Land	15.8				1		1																					
Artificial/Aquatic - Wastewater Treatment Areas	15.6				1																							1
Artificial/Aquatic - Water Storage Areas (over 8ha)	15.1				1																							1
Artificial/Marine - Mari/Brackishculture Ponds	15.13																											1
Artificial/Marine - Mariculture Cages	15.12													1														
Artificial/Marine - Marine Anthropogenic Structures	15.11																											1
Artificial/Terrestrial	14		1		1			1	1	1	1	1	1									1						
Artificial/Terrestrial - Arable Land	14.1				1			1																				
Artificial/Terrestrial - Pastureland	14.2				1				1	1	1	1																
Artificial/Terrestrial - Plantations	14.3				1			1																				
Artificial/Terrestrial - Rural Gardens	14.4		1		1			1																				
Artificial/Terrestrial - Subtropical/Tropical Heavily Degraded Former Forest	14.6				1			1					1									1						

Artificial/Terrestrial - Urban Areas	14.5		1		1																							
Back Slope	9.8.2													1														
Caves and Subterranean Habitats (non-aquatic)	7													1														
Caves and Subterranean Habitats (non-aquatic) - Caves	7.1													1														
Caves and Subterranean Habitats (non-aquatic) - Other Subterranean Habitats	7.2													1														
Coastline - Intertidal Mud, Sand or Salt Flats	10.4			1																								
Coastline - Rocky Shores (includes rocky offshore islands and sea cliffs)	10.1			1																								
Coastline - Sand, Shingle or Pebble Shores (incl. sand bars, spits, sandy islets, dune systems)	10.2			1																								
Desert	8			1																								
Desert - Cold	8.3			1																								
Desert - Hot	8.1			1																								
Desert - Temperate	8.2			1																								
Foreslope (Outer Reef Slope)	9.8.3													1														
Forest	1												1						1	1	1		1	1	1	1	1	
Forest - Boreal	1.1												1						1	1	1		1	1	1	1		
Forest - Subantarctic	1.3																		1	1	1		1	1	1	1		

Forest - Subarctic	1.2																		1	1	1		1	1	1	1		
Forest - Subtropical/Tropical Dry	1.5												1						1	1	1		1			1		
Forest - Subtropical/Tropical Mangrove Vegetation Above High Tide Level	1.7																									1	1	
Forest - Subtropical/Tropical Moist Lowland	1.6												1						1	1	1		1			1		
Forest - Subtropical/Tropical Moist Montane	1.9																		1	1	1		1	1	1			
Forest - Subtropical/Tropical Swamp	1.8																									1		
Forest - Temperate	1.4												1						1	1	1		1	1	1	1		
Grassland	4					1			1	1	1	1			1			1										
Grassland - Subantarctic	4.3					1			1	1	1	1						1										
Grassland - Subarctic	4.2					1			1	1	1	1						1										
Grassland - Subtropical/Tropical Dry	4.5					1			1	1	1	1						1										
Grassland - Subtropical/Tropical High Altitude	4.7					1			1	1	1	1						1										
Grassland - Subtropical/Tropical Seasonally Wet/Flooded	4.6					1			1	1	1	1			1			1										
Grassland - Temperate	4.4					1			1	1	1	1			1			1										
Grassland - Tundra	4.1					1			1	1	1	1						1										
Hard Substrate	11.1.1													1														
Inter-Reef Rubble Substrate	9.8.6													1														

Inter-Reef Soft Substrate	9.8.5													1														
Introduced vegetation	16				1			1	1																			
Lagoon	9.8.4													1														
Marine Coastal/Supratidal - Coastal Brackish/Saline Lagoons/Marine Lakes	13.4														1												1	1
Marine Coastal/supratidal - Coastal Caves/Karst	13.2													1														
Marine Coastal/Supratidal - Coastal Freshwater Lakes	13.5																											1
Marine Coastal/Supratidal - Coastal Sand Dunes	13.3			1																								
Marine Coastal/Supratidal - Sea Cliffs and Rocky Offshore Islands	13.1			1																								
Marine Deep Benthic - Abyssal Mountain/Hills (4,000-6,000m)	11.3													1														
Marine Deep Benthic - Abyssal Plain (4,000-6,000m)	11.2													1														
Marine Deep Benthic - Continental Slope/Bathyl Zone (200-4,000m)	11.1													1														
Marine Deep Benthic - Deep Sea Vents (Rifts/Seeps)	11.6													1														

Marine Deep Benthic - Hadal/Deep Sea Trench (>6,000m)	11.4													1														
Marine Deep Benthic - Seamount	11.5													1														
Marine Intertidal	12			1											1												1	1
Marine Intertidal - Mangrove Submerged Roots	12.7																										1	
Marine Intertidal - Mud Flats and Salt Flats	12.4			1											1													
Marine Intertidal - Rocky Shoreline	12.1			1																								
Marine Intertidal - Salt Marshes (Emergent Grasses)	12.5														1													1
Marine Intertidal - Sandy Shoreline and/or Beaches, Sand Bars, Spits, Etc	12.2			1																								
Marine Intertidal - Shingle and/or Pebble Shoreline and/or Beaches	12.3			1																								
Marine Intertidal - Tidepools	12.6																											1
Marine Neritic	9													1														
Marine Neritic - Coral Reef	9.8													1														
Marine Neritic - Estuaries	9.10													1														
Marine Neritic - Macroalgal/Kelp	9.7													1														
Marine Neritic - Pelagic	9.1													1														
Marine Neritic - Seagrass (Submerged)	9.9													1														

Marine Neritic - Subtidal Loose Rock/pebble/gravel	9.3													1														
Marine Neritic - Subtidal Muddy	9.6													1														
Marine Neritic - Subtidal Rock and Rocky Reefs	9.2													1														
Marine Neritic - Subtidal Sandy	9.4													1														
Marine Neritic - Subtidal Sandy-Mud	9.5													1														
Marine Oceanic	10													1														
Marine Oceanic - Abyssopelagic (4000-6000m)	10.4													1														
Marine Oceanic - Bathypelagic (1000-4000m)	10.3													1														
Marine Oceanic - Epipelagic (0-200m)	10.1													1														
Marine Oceanic - Mesopelagic (200-1000m)	10.2													1														
Other	17													1														
Outer Reef Channel	9.8.1													1														
Rocky areas (eg. inland cliffs, mountain peaks)	6			1																								
Savanna	2												1			1	1											
Savanna - Dry	2.1												1			1	1											
Savanna - Moist	2.2												1			1	1											
Shrubland	3														1	1	1	1										
Shrubland - Boreal	3.3															1	1	1										
Shrubland - Mediterranean-type Shrubby Vegetation	3.8															1	1	1										
Shrubland - Subantarctic	3.2															1	1	1										

Shrubland - Subarctic	3.1															1	1	1										
Shrubland - Subtropical/Tropical Dry	3.5															1	1	1										
Shrubland - Subtropical/Tropical High Altitude	3.7															1	1	1										
Shrubland - Subtropical/Tropical Moist	3.6														1	1	1	1										
Shrubland - Temperate	3.4														1	1	1	1										
Soft Substrate	11.1.2													1														
Unknown	18													1														
Wetlands (inland)	5													1	1											1	1	1
Wetlands (inland) - Alpine Wetlands (includes temporary waters from snowmelt)	5.11														1													1
Wetlands (inland) - Bogs, Marshes, Swamps, Fens, Peatlands	5.4														1													1
Wetlands (inland) - Freshwater Springs and Oases	5.9																											1
Wetlands (inland) - Geothermal Wetlands	5.12																											1
Wetlands (inland) - Karst and Other Subterranean Hydrological Systems (inland)	5.18													1														
Wetlands (inland) - Permanent Freshwater Lakes (over 8ha)	5.5																											1

Wetlands (inland) - Permanent Freshwater Marshes/Pools (under 8ha)	5.7														1													1
Wetlands (inland) - Permanent Inland Deltas	5.13														1											1		1
Wetlands (inland) - Permanent Rivers/Streams/Creeks (includes waterfalls)	5.1																											1
Wetlands (inland) - Permanent Saline, Brackish or Alkaline Lakes	5.14																											1
Wetlands (inland) - Permanent Saline, Brackish or Alkaline Marshes/Pools	5.16																											1
Wetlands (inland) - Seasonal/Intermittent Freshwater Lakes (over 8ha)	5.6														1											1		1
Wetlands (inland) - Seasonal/Intermittent Freshwater Marshes/Pools (under 8ha)	5.8														1											1		1
Wetlands (inland) - Seasonal/Intermittent Saline, Brackish or Alkaline Lakes and Flats	5.15														1												1	1
Wetlands (inland) - Seasonal/Intermittent Saline, Brackish or Alkaline Marshes/Pools	5.17														1												1	1

Wetlands (inland) - Seasonal/Intermittent /Irregular Rivers/Streams/Creeks	5.2																											1
Wetlands (inland) - Shrub Dominated Wetlands	5.3														1													1
Wetlands (inland) - Tundra Wetlands (incl. pools and temporary waters from snowmelt)	5.10														1													1

Appendix V: The Watershed Exploration Tool: a web-portal for exploring results.

A “Watershed Exploration Tool”, is available for users to explore the results from this project. This is a web-based tool that provides a platform for viewing and interrogating results of the spatial modelling for this project. This tool was first developed under a precedent project that covered additional regions in the Mekong and Andes watersheds. The analyses for these regions were conducted both using the Global Environment Outlook GEO-4 (UNEP, 2007) and regional scenarios.

The core functionality allows users to navigate using online web mapping to their region of interest (see Figure A1) and compare watersheds for:

i) biodiversity and ecosystem function importance for baseline (2005) and future (2050) scenarios,
ii) change between these time periods and,
iii) trade-offs and future threats.

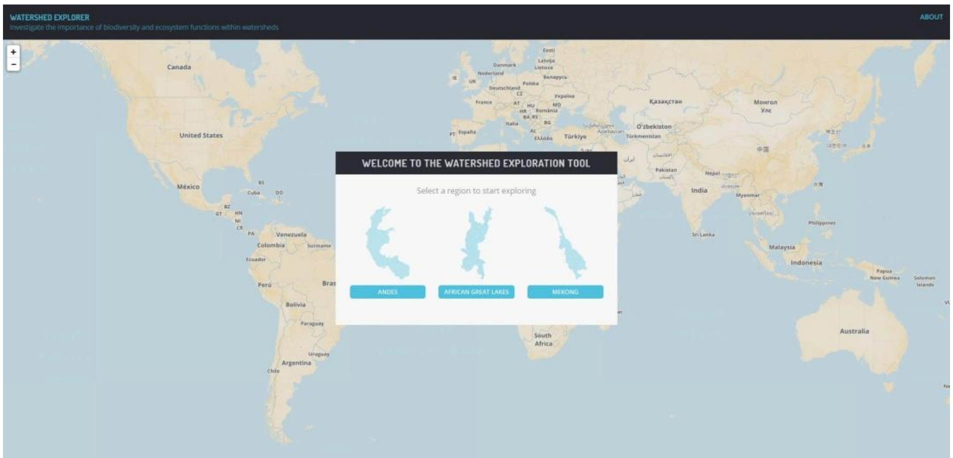

Figure A1: Screenshot of the opening page for Watershed Exploration Tool where the user can choose to explore results for their region of interest.

The tool provides a variety of additional features:

- Options to focus on subsets most relevant to their interest:
  - Biodiversity (threatened species, amphibians, mammals or birds) and
  - Ecosystem function provision (commodity provision, wild provision or regulatory functions provision).
- Filters to highlight watersheds according to:
  - Their score for their chosen metric (e.g. watersheds with highest baseline scores for commodity provision)
  - Overlap with protected areas,
  - Known pressures from extractives and dams.

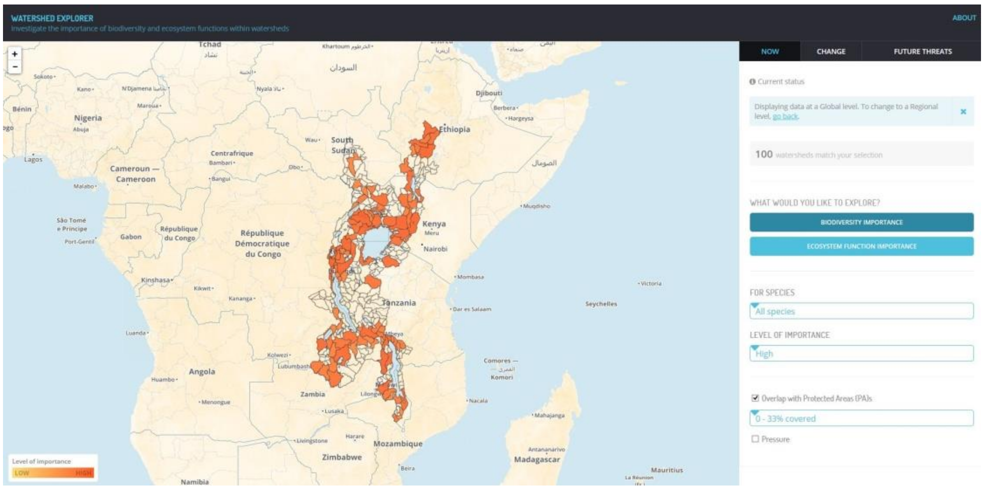

Figure A2: Screenshot of the Watershed Exploration Tool showing watersheds in the Great Lakes of Africa for the baseline time-period. In this case drop-down filters were used to select watersheds with a high biodiversity score for all species combined (amphibians, birds and mammals), but with a low proportional overlap with protected areas.

The variety of available filters (see Figure A2), allow the user to select watersheds of interest. Further additional information is available in the background information for each individual watershed, which the user can click to download as a PDF Information sheet (see Figure A3).

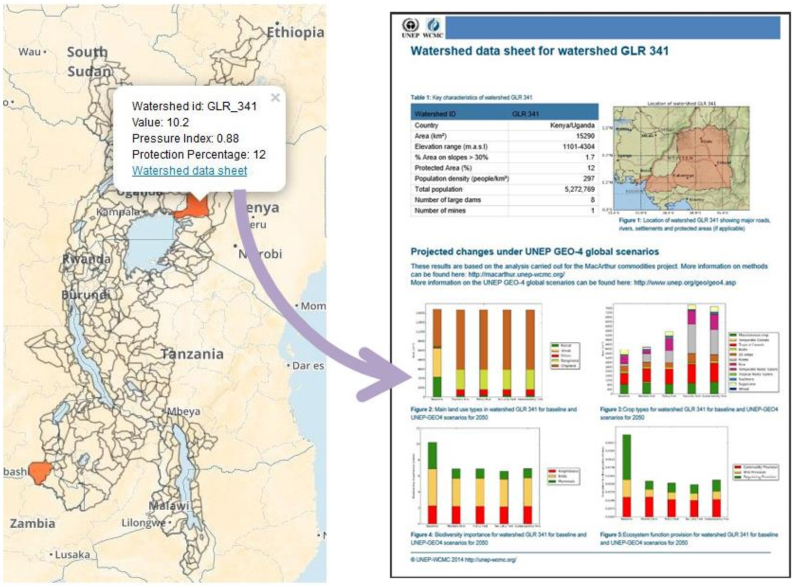

Figure A3: Showing watershed selection with hyperlink to the downloadable PDF data sheet for this watershed.

For users unfamiliar with this project there is an “About” page which provides a succinct background on both the aims and limitations of the tool and the links to further information and this report.

The Watershed Exploration Tool can be accessed from this link: http://macarthur.unep-wcmc.org/

Appendix VI: Watershed boundaries with protected areas and Key Biodiversity Areas for the Lake Victoria Basin.