Potential Climate Change Impacts in Conservation Landscapes of the Albertine Rift

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Executive Summary

From 2007-09, the Wildlife Conservation Society conducted the Albertine Rift Climate Change Assessment, an exploratory study funded by the John D. and Catherine T. MacArthur Foundation to develop understanding of potential impacts of anthropogenic climate change challenges on wildlife conservation in one of Africa's most biodiverse landscapes. The project objectives were to quantify conservative-to-extreme predictions of regional climate change across the Albertine Rift, to assess future impacts of climate change and estimate the future distribution of biodiversity in the Albertine Rift, and to develop our findings in partnership with the wider biodiversity conservation community.

Results of the environmental modeling component of the project are detailed in this whitepaper report. A companion whitepaper, *Climatological Assessment of the Albertine Rift for Conservation Applications*, focuses on climatology. The modeling approach was designed to generate a suite of products which, taken together, provide comprehensive guidance on the potential impacts of anthropogenic climate change on biodiversity in the Albertine Rift. We looked specifically at climatic, environmental and ecological changes at three time points in the future - 2030, 2060 & 2090, and contrasted them with a 1990 historical baseline. The model predictions presented here are based on the SRES A2 greenhouse gas emissions scenario, and provide a habitat-focused view of the potential impacts of climate change on biodiversity. Spatial analyses illustrate the potential future climate, ecosystem function and crop yields for the entire Albertine Rift, and more specifically for seven sub-regional case study sites selected for their high importance to conservation. Due to caveats inherent in climate prediction, we caution that neither the modeling products nor inference derived from them should be considered and responded to as explicit forecasts. Rather, they provide Albertine Rift conservation managers, regional stakeholders and researchers with an initial set of baseline information and guidance tools to assist in developing adaptive management for biodiversity conservation in the changing climates of the 21st century.

Acknowledgements:

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In addition, the following people have made extremely significant contributions to the technical analysis conducted during the project:

Dr. Ruth Doherty for her expertise in Lund-Potsdam Jenna ecosystem modeling

Dr. Philip Thornton for his expertise in Global Climate Model downscaling and crop yield modeling

Dr. Andrew Plumptre, for organizing climatological data collection

Also, we are grateful to the organizations and individuals who contributed climatological data for analysis, which was invaluable for the climatological assessment.

Contents

1. INTRODUCTION

1a. The Albertine Rift – overview and significance

The Albertine Rift is the western branch of the Great Rift Valley of Africa It extends from the northern end of Lake Albert to the southern end of Lake Tanganyika, and encompasses lands flanking both sides of the rift and straddling several countries: The Democratic Republic of Congo, Uganda, Rwanda, Burundi, Tanzania and Zambia (Figure 1). It is a region of exceptional topographic and ecological complexity, encompassing the glacierized Rwenzori Mountains, the great lakes of the rift valley floor, and the continental ecotone of the Congo Rainforest and East African savannah biomes, among numerous other features.

The Albertine Rift is recognized to be one of the most important regions for the conservation of Africa's biodiversity. With numerous major protected areas currently established, it is home to many endemic species including the mountain gorilla and golden monkey, 42 species of birds, and many reptiles, amphibians, fish, invertebrates, and plants. It contains more vertebrate species than any other region on mainland Africa, and is home to some 40-50 million people, the large majority of whom are subsistence farmers (Plumptre et al., 2002, Plumptre et al., 2007).

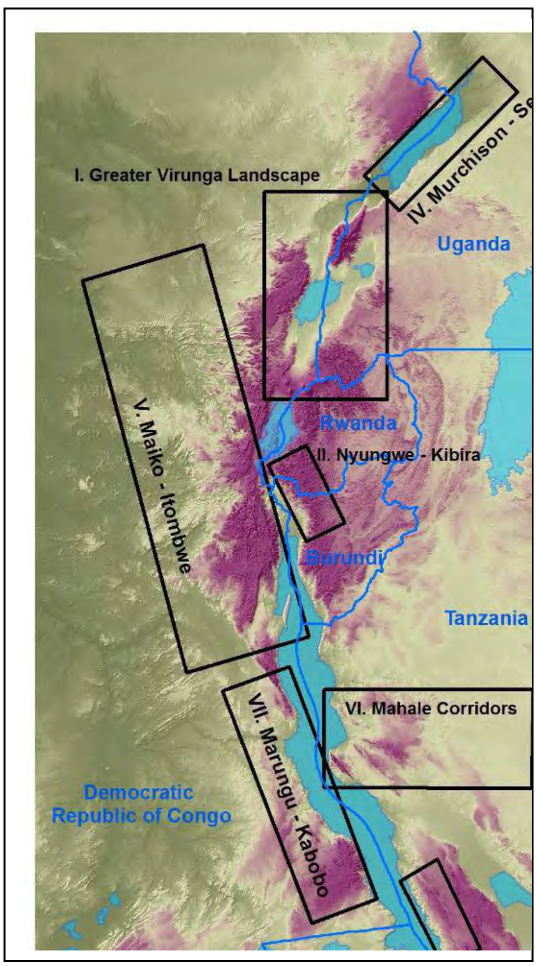

Figure 1: Relief map of the Albertine Rift region showing national boundaries and core biodiversity conservation landscapes examined in this study. Darkening purple and green shades indicate increasing highland and decreasing lowland elevations, respectively. Major water bodies are shown in blue.

1b. Project purpose and outputs

Until very recently, climate change has largely been absent from consideration among priorities for biodiversity conservation in the Albertine Rift. As one of a series of measures aimed at addressing this shortcoming, in 2007 the John D. and Catherine T. MacArthur Foundation funded the Albertine Rift Climate Assessment, a two-year project by the Wildlife Conservation Society (WCS) to conduct an initial assessment of climate change and it potential impacts along the Albertine Rift corridor and within its key protected areas in particular. The purpose of this report is to summarize and evaluate information generated by environmental modeling of future climatic and biotic changes projected for the Albertine Rift, and to offer guidance on the potential use of this information by all interests concerned with conservation. As a pilot study on climate change for the Albertine Rift region, this analysis is by design a relatively macro-scale approach and does not offer focus on any individual species, biomes or protected areas. Future work will utilize the findings and modeled output of this study as a starting point towards more applied analysis incorporating model output into conservation planning.

This white paper is the second of two that collectively present and describe the results and findings from the WCS Albertine Rift Climate Assessment. The companion study, ***Climatological Assessment of the Albertine Rift for Conservation Applications*****,** summarizes the state of knowledge of regional climatology (Seimon and Picton Phillipps 2009). A third component of this project's output is an online archive of modeling products, all freely available for download at the project website by registered users, along with documents detailing the modeling approach and methodology, project reports and other project materials. The website link is at:
http://programs.wcs.org/Resources/Downloads/tabid/2801/Default.aspx

2. ENVIRONMENTAL MODELING

The WCS Climate Assessment project utilized a multi-step methodology to generate landscape modeling products spawned from global climate model projections. This section provides an overview of the modeling component of the Climate Assessment project, and the model approach is detailed in Annex 2. Complete detail on the modeling methodology, including specialized computer programming scripts, is provided at the project website linked above.

2a. Greenhouse gas emissions scenarios utilized

The core datasets that underpin the entire data analysis component are the outputs from global climate models (GCM) simulations incorporating observed and projected atmospheric greenhouse gas emissions as developed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, completed in 2007. GCM output containing predications for the 21st century from three different IPCC Special Report Emission Scenarios (SRES; IPCC 2007) were downloaded and processed for this study. These are the A1B, A2 and B1 scenarios, which have been the focus of model inter-comparison studies. According to the IPCC Fourth Assessment Report Summary for Policy Makers (IPCC 2007), the characteristics of each are as follows:

- The SRES A1B scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. Technological change in the energy system balances fossil intensive and non-fossil energy sources, where balanced is defined as not relying too heavily on one particular energy source
- The SRES A2 scenario describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.
- The SRES B1 scenario describes a convergent world with the global population that peaks in mid-century and declines thereafter, with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

Although data was processed for all three, the discussions and interpretation of modeled product presented in this report are restricted to the more pessimistic A2 scenario for the following reasons. First, recent evidence suggest that present day emission levels have already deviated well above the most severe SRES cases considered for the 2007 IPCC Fourth Assessment Report, suggesting that the more conservative scenarios are increasingly unlikely to be applicable. Second, while climatic signals are mostly of the same sign for both scenarios, they are significantly amplified under the A2 scenario relative to the A1B and B1 scenarios, thus making changes more apparent, and consequentially, more readily identifiable and understandable. Therefore, with little evidence available at present to suggest that the global economic trajectory will see a replacement of fossil fuels with other energy sources for many decades to come, we feel that the best choice is to constrain to the discussion here to the A2 scenario. However, to enable comparison, the full suite of model products from based on each of the 3 scenarios is available for download from the project website.

2b. Modeling methodology

There are five 5 distinct stages to the data analysis: (1) data acquisition and pre-processing; (2) climate model downscaling; (3) ecosystem modeling; (4) crop modeling; and (5) spatial analysis. This sequence is outlined in Figure 2. A full technical description of the steps taken to process the low resolution global climate data are given in Annex 1, while an overview is provided in this section.

First, data from the low resolution GCM multi-model global ensembles were extracted for the Albertine Rift region for the period 1990 – 2090. These datasets were used as input to a statistical downscaling procedure which produced a set of medium resolution climate model data for the same period with a spatial resolution of approximately 50km. These datasets were used in their raw state to provide predictions of climate in the Albertine Rift at 2030, 2060 & 2090, and also as input to ecosystem and crop yield modeling, performed using the Lund-Potsdam-Jena (LPJ) and Decision Support System for Agro-technology Transfer (DSSAT) models, respectively. The models are described in Sitch et al (2003) for the LPJ and Thornton et al. (2009) for DSSAT, and discussed further in Annex 1. A summary table of raw input data and analytical and informational outputs is provided in Annex 2.

It is important to specify that from a temporal perspective what was actually extracted were the monthly means calculated from the raw GCM output data for 10 years either side of the year of interest. The reason for calculating monthly means is to eliminate single year anomalies that may occur in model simulations. For example, the value that is provided in the data for January temperature for 2060 is actually the mean value of temperature in January for all the years between 2050 and 2069. As such, parameters values for a given year were calculated over the following periods shown in parentheses: for 1990 (1980–1999); for 2010 (2020-2039); for 2060 (2050-2069) and for 2090 (2080–2099).

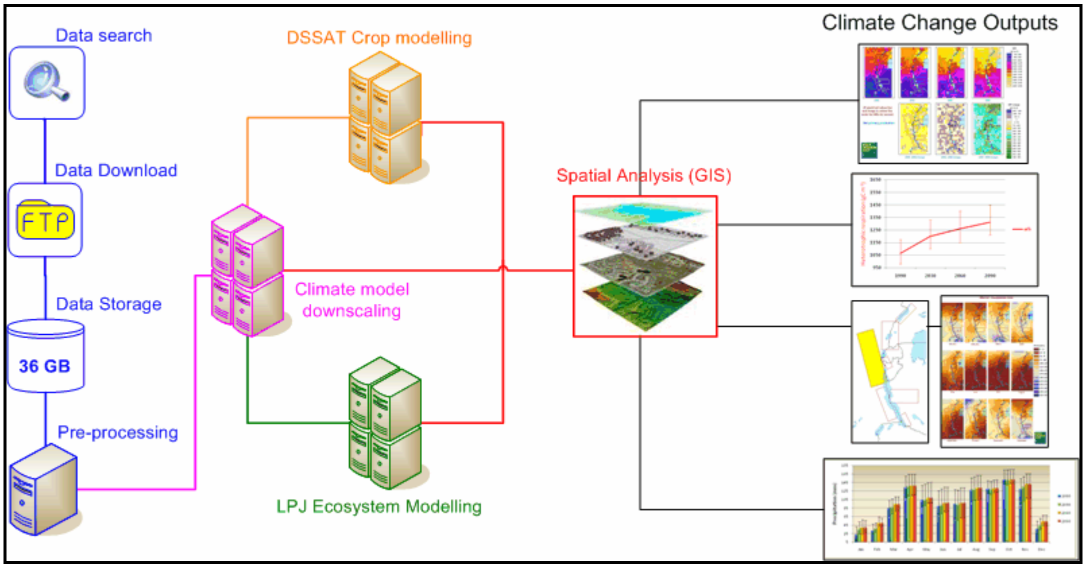

Figure 2: Schematic diagram demonstrating the procedure used to generate ecologically meaningful products specific to the Albertine Rift study domain from raw, low resolution GCM output.

2c. Model products

The diverse suite of products generated from the various modeling exercises for this study can be classified under the 5 general categories summarized below.

1. Climatological variables

a. Monthly mean temperature (°C)
b. Monthly mean precipitation amount (mm)
c. Monthly mean cloud cover (percent of sky coverage)

2. Carbon Fluxes

Expressed in units of grams of carbon per square meter (g C m^{-2})

a. Net Primary Production (NPP) - Production of organic matter from atmospheric (or aquatic) carbon dioxide by plants in an ecosystem minus losses of carbon resulting from plant respiration
b. Land-Atmosphere flux - Change in carbon storage between terrestrial ecosystems and the atmosphere

c. Carbon Loss from Fire - Amount of carbon emitted to the atmosphere each year through vegetation burning
d. Heterotrophic respiration (Rh) - Amount of carbon released through the decomposition of dead organic matter

3. Carbon Pools

Expressed in units of kilograms of carbon per square meter (kg C m^{-2})

a. Vegetation Carbon - Amount of carbon stored in vegetation
b. Soil Carbon - Amount of carbon stored in the soil
c. Litter Carbon - Amount of carbon stored in dead organic matter
d. Annual Total Carbon – the sum of Vegetation, Soil & Litter carbon

4. Hydrological Variables

a. Total Runoff (mm) - Sum of direct runoff and base flow arriving at a drainage channel for discharge via streamflow.
b. Actual Evapotranspiration (mm) - Quantity of water actually removed from a surface due to the processes of evaporation and transpiration

5. Vegetation and agriculture

a. Annual Phaseolus Bean Yield (kg ha^{-2})
b. Annual *Brachiaria decumbens* Yield (kg ha^{-2})
c. Annual Maize Yield (kg ha^{-2})
d. Fractional Cover of Plant Functional Type (%) Based on the modelled results of the above variables and allometric relationships with Plant Functional Types (PFT), the spatial percentage cover for the following plant functional types can be modelled, allowing an assessment of vegetation and habitat change as a result of climate change. The PFT types are coded as follows:

trbe – Tropical Broadleaved Evergreen Tree
trbr – Tropical Broadleaved Raingreen Tree
tene – Temperate Needleaved Evergreen Tree
tebe – Temperate Broadleaved Evergreen Tree
tebs – Temperate Broadleaved Summergreen Tree
c3pg – c3 Perennial Grass
c4pg – c4 Perennial Grass

The biotic and environmental variables are calculated for benchmark years of 1990 (2000 for the modeled crops), 2030, 2060 and 2090 based on downscaled global climate model parameters means for the 20-year period centered upon each focal year. These parameters were generated for the entire Albertine Rift domain, with subsets then generated for each of the sub-regional Albertine Rift conservation landscapes evaluated in this study.

3. MODELING RESULTS

The following sections present quantified summaries of key environmental parameters in model output under the A2 emissions scenario for the key benchmark years, along with some interpretive discussion on possible significance to biodiversity and ecological systems. Discussion and interpretation on carbon pool characteristics and change over time is slightly outside the primary focus of this study (and of the analysts' current expertise), so will be more properly assessed in future work.

In presenting this content and its often compelling, at times alarming, predictions we also need to convey a high degree of caution, and be didactic in declaring that we believe that neither the quantities specified, nor the interpretations that we offer, can be confirmed to be sufficiently reliable to serve as the basis of much direct conservation action in the short-term. Discussion on appropriate use will follow in Section 5.

3a. Environmental changes across the entire Albertine Rift domain

In this section the focus is the broad regional scale of the entire Albertine Rift domain, defined for this work as displayed in Figure 1 by a rectangle extending from 10° S to 3°N Latitude and 26° to 33° E Longitude. In Section 3b the focus moves to the mesoscale, where we perform similar evaluations for seven key sub-regions of recognized importance for biodiversity conservation. Summary statistics listing the maximum, mean and minimum pixel values of selected parameters for each of the benchmark year throughout the modeled domain are presented below in Table 1. Spatial mapping of selected parameters from LPJ model simulations is also provided in this section; the climate parameters (temperature, precipitation and cloud cover) are presented in the companion study on climatology.

Temperature

In the A2 model simulations Temperature increases are significant and occur at an accelerating pace across the Albertine Rift domain during the course of the 21st century. Spatial variation of temperature is fixed in place on the mesoscale, reflecting the control of terrain elevation over surface temperature. At the broader regional scale, small spatial variability in thermal seasonality is evident further from the Equator especially across the southern part of the Albertine Rift domain. It is noteworthy that temperature extrema in the mapped domain increase at the same rate as the domain-averaged mean. This identifies unambiguously that no locales will remain unaffected by strong and sustained warming relative to current conditions.

Interpretation: In terms of biodiversity, the most direct consequence of this trend would be to coerce individual species and species assemblages to track their favored thermal envelopes upward to higher terrain. The scale of the net displacement is daunting, however. Given that temperature change as a function of elevation in tropical atmospheres average 5-6°C per km, the net region-wide thermal increase of 3.6°C under the A2 scenario translates to a very large upward displacement of 600-720 meters. It follows that human activities and settlement will likewise display a comparable drive for uphill migration in order to track current climatic envelopes. Furthermore, since landforms characteristically taper in area as a function of elevation, this also represents growing spatial constriction and intensifying competition for favorable habitat over time.

Precipitation

In the A2 model simulations Precipitation changes are both highly significant and spatially heterogeneous across large parts of the Albertine Rift domain during the course of the 21st century. At regional scales two patterns of change stand out. The first is an overall increase in net annual precipitation. Relative to the 1990 baseline, rainfall increases by 3%, 7% and 17% in 2030, 2060 and 2090, respectively. The initially slow increase is a cause for concern since proportionally greater temperature increases over the same period will shift the hydrological balance towards drying through increased evaporative loss. The second pattern is temporal redistribution in the annual fraction of rainfall associated with the twin wet seasons that characterized rainfall over much of the Albertine Rift. The model output indicates that the largest increases in rainfall amount will occur from mid-century onward, when a large increase in the magnitude of Nov-Dec rainfall will occur while little net change is evident in the March April period. This is amply evident by comparing the

1990 baseline data for the April and November peak pluvial months of the twin wet seasons (see Annex 1). These are remarkably similar in terms of rainfall amount and spatial distribution, yet by 2060, and especially by 2090 major asymmetry becomes evident as November becomes wetter by an average of 1-2 mm of rainfall per day while April remains almost unchanged.

Interpretation: With greatly increased evaporative loss under the strongly warming climatic regime, this pattern implies increasing hydrological stress during the currently bountiful Feb-May wet season, whereby a failure of the rains in a given year at this time preceding the annual drought could have catastrophic consequences. The recent experience of this pattern in 2009 is particularly sobering in this regard, and could be taken as a harbinger of challenges ahead. As discussed in the companion report focusing on climatology (Seimon and Picton Philipps 2009), redistribution in annual rainfall concordant with this pattern is already apparent at Mahale on Lake Tanganyika, though whether this represents early establishment of the pattern depicted in the model output or simply climatic variability cannot yet be ascertained.

		1990	2030	2060	2090	
Mean annual temperature¥	*Max*	26.0	27.0	28.1	29.7	°C
	Mean	**22.7**	**23.6**	**24.7**	**26.3**	
	Min	15.0	16.0	17.1	18.7	
Mean annual precipitation¥	*Max*	1887	1900	1968	2098	mm
	Mean	**1199**	**1233**	**1287**	**1406**	
	Min	821	875	938	1057	
Mean annual cloud cover¥	*Max*	82.6	82.4	81.7	81.9	%
	Mean	**67.2**	**67.4**	**66.9**	**67.1**	
	Min	42.4	43.2	43.2	43.4	
Annual runoff¥	*Max*	723	760	871	986	mm
	Mean	**264**	**286**	**327**	**433**	
	Min	43	28	50	127	
Annual net primary productivity¥	*Max*	1520	1639	1748	1847	$gC\ m^{-2}$
	Mean	**1060**	**1150**	**1242**	**1331**	
	Min	724	796	868	956	
Annual heterotrophic respiration¥	*Max*	1278	1474	1631	1681	$gC\ m^{-2}$
	Mean	**916**	**1007**	**1105**	**1203**	
	Min	582	673	770	865	
Annual total carbon¥	*Max*	59.3	57.6	56.7	56.1	$kg\ C\ m^{-2}$
	Mean	**33.0**	**33.1**	**32.9**	**32.8**	
	Min	19.0	19.6	20.2	20.4	
Bean Yield§	*Max*	1497	1443	1387	1332	$kg\ ha^{-2}$
	Mean	**799**	**754**	**721**	**627**	
	Min	1	11	73	67	
Maize Yield§	*Max*	3531	3539	3402	3111	$kg\ ha^{-2}$
	Mean	**1102**	**1103**	**1098**	**1025**	
	Min	32	46	46	44	
Brachiaria Yield§	*Max*	4147	4328	4577	4957	$kg\ ha^{-2}$
	Mean	**1663**	**1730**	**1884**	**1943**	
	Min	2	4	6	15	

¥Baseline reference year = 1990, §Baseline reference year = 2000

Table 1: Summary of climate, ecosystem and crop yield change under the A2 emissions scenario for the entire Albertine Rift domain. Color shading of increasing intensity aids visual identification of the rank of parameter magnitude within the sequence of time steps.

Cloud Cover

In the A2 model simulations, net Cloud cover across the Albertine Rift domain remains almost invariant around 67% for all years assessed, but spatial changes nonetheless are significant and increase markedly during the course of the century as internal redistribution of cloudiness patterns develop. Monthly cloud cover changes mostly fall within the range of +/- 2% in 2030 relative to the 1990 baseline, though with some spatial coherence indicating slight moistening in the south and drying in the north. More significant changes become apparent by 2060, when cloud cover reduction of 3-5% in April and May are widespread in the north, suggesting that the wet season termination will tend to occur earlier in the season over time. By 2090 cloud cover during the April wet season peak is reduced region wide, indicative of the trend towards a drier season evident in precipitation amount too. A large departure relative to the present is also depicted for 2090 in the months of November and December throughout the southeastern part of the domain. Here, cloud cover increases significantly, by more than 5%, in association with greatly increased rainfall, yet these factors nonetheless fail to dampen the magnitude of thermal increase which is still more than 3°C above the 1990 baseline.

Interpretation: From this it can be inferred that while climatic conditions will become oppressively warm and humid, and considerably more so than currently experienced, cloud coverage is less likely to represents this with major changes. Not revealed in the model output, however, are trends in altitude of orographic clouds that are critically important in mountain environments to sustaining cloud forest ecosystems and species assemblages. A warming climate would generally be associated with a lifting of the mean cloud base elevation, such as has been reported in Costa Rican montane cloud forests (Pounds and Crump 1999); for the Albertine Rift the magnitude of warming projected by the end of the century under the A2 scenario would translate to a rise in mean orographic cloud bases of at least several hundred meters.

Runoff

In the A2 model simulations net Annual Runoff changes are generally positive and increase very significantly over time, though are also highly heterogeneous across space throughout the Albertine Rift domain during the course of the 21st century. The spatial characteristics of change reveal several patterns of particular interest relative to the 1990 baseline (Figure 3). First, by 2030 runoff initially decreases in the northern part of the rift domain while increasing slightly to the south. The deficits in the north reverse by 2060 while the central highlands flanking the rift now exhibit large positive anomalies. Finally, by 2090 the entire domain has increased runoff, with very large runoff increases broadly centered over the heart of the rift, except along Lake Tanganyika

Interpretation: The near-term indications of initial reductions in runoff across the northern regions of the rift corridor in 2030 are of concern. This implies a multidecadal period of reduced river flows and lake levels, including for Lakes Edward, George and Albert, in some of the most important conservation landscapes of Albertine Rift. In contrast, by 2090 runoff across the entire domain could be characterized as excessive relative to current conditions, averaging 64% greater than the 1990 baseline across the domain. Such changes would undoubtedly alter the riverine and lacustrine hydrology, erosion and siltation rates, and ground water recharge radically relative to the present virtually everywhere in the rift region, with cascading effects upon species and ecosystems. By late in the century, strongly increasing trends are predicted for both evaporation and runoff, opposing hydrological factors that influence river flows and lake levels. Large magnitude fluctuations in all water bodies relevant to present conditions would therefore appear likely to occur on a seasonal and inter-annual basis, with greatly increased potential for extremes of high and low water compared to past experience.

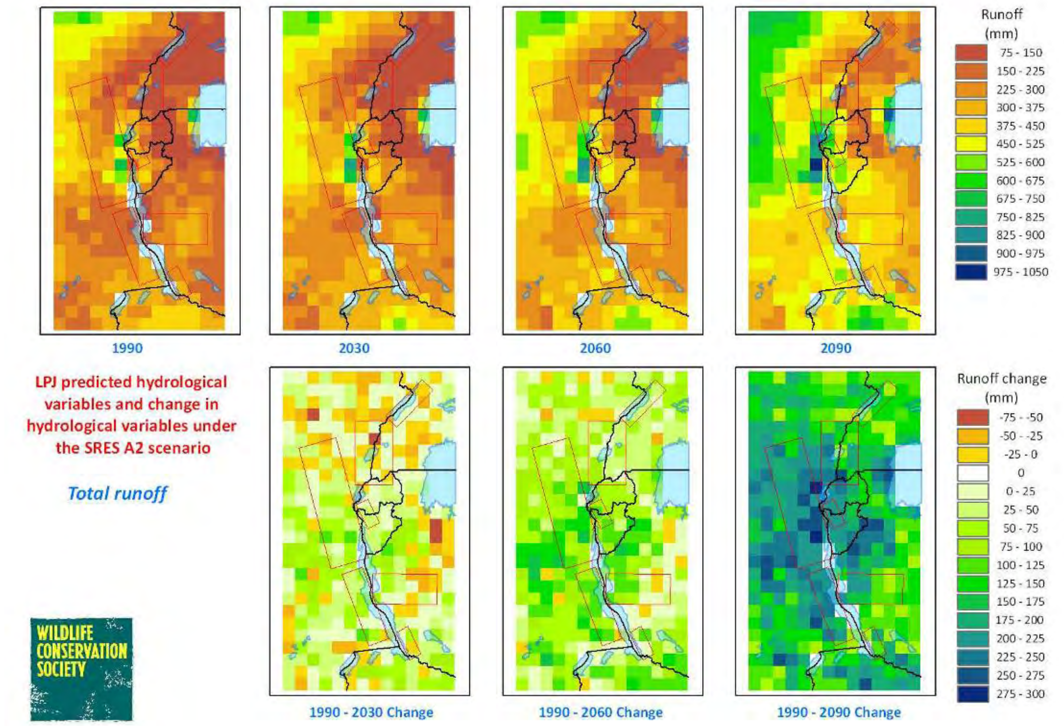

Figure 3: Annual Total Runoff and change relative to 1990 historical baseline from LPJ model simulations in 2030, 2060 and 2090 under the A2 emissions scenario

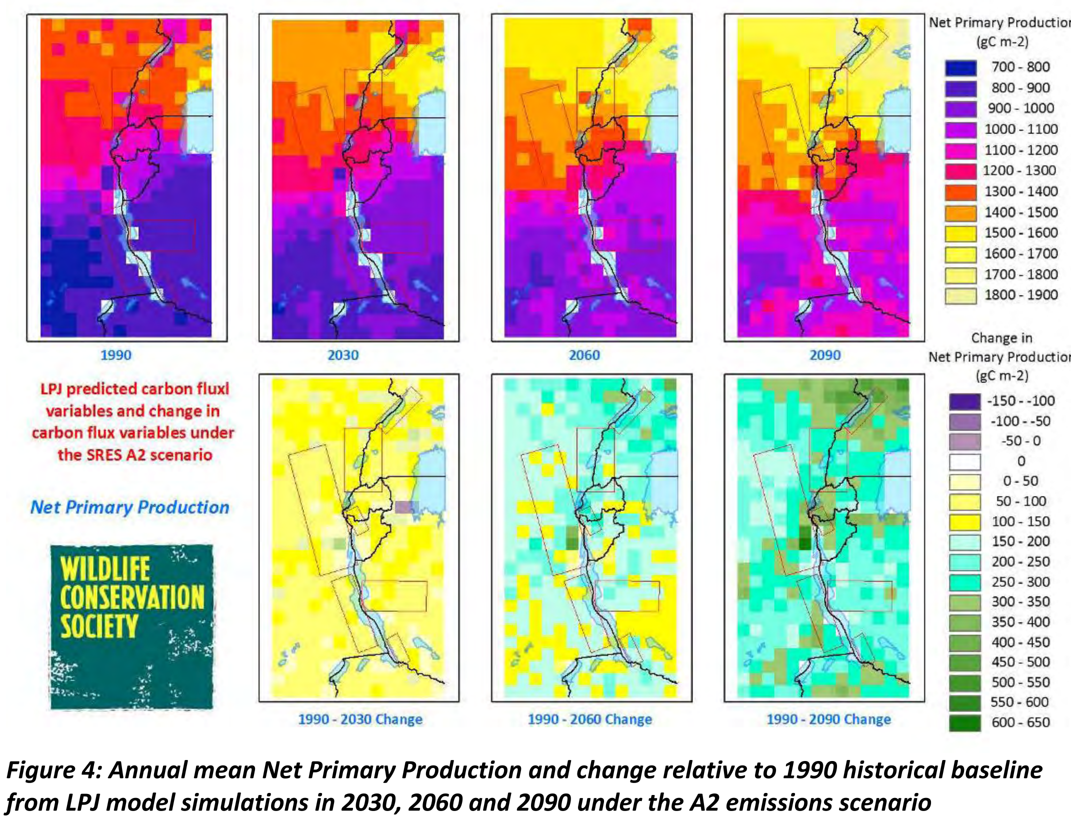

Figure 4: Annual mean Net Primary Production and change relative to 1990 historical baseline from LPJ model simulations in 2030, 2060 and 2090 under the A2 emissions scenario

Net Primary Production

In the A2 model simulations mean Annual Net Primary Production exhibits a strong, nearly monotonic upward trend across the Albertine Rift domain during the course of the 21st century. The increase averages +0.28% per year, yielding a net increase of 25.6% in 2090 relative to the 1990 baseline. The spatial changes distribution of these changes is shown in Figure 4.
There is initially little variation evident as values increase to 2030. By 2060 the patterns diverge as the northern areas experience proportionally greater increases. By 2090 the entire domain shows significant increases, with the north now sustaining very high values.

***Interpretation*:** As such the increase in Net Primary Production tracks the relatively steady temperature increases, but might also reflect the increased CO_2 fertilization effect facilitating photosynthesis due to the sustained rise of carbon dioxide concentration under the A2 scenario. The Net Primary Production increases and attendant rise in vegetation carbon (not shown, but available at the project website) would seemingly represent both opportunities for wildlife, through greater food availability and richer habitat, and threats, through proliferation of opportunistic and invasive species as well as the potential for greater fuel load for fires.

Heterotrophic Respiration

In the A2 model simulations mean net Annual Heterotrophic Respiration (Rh) similarly exhibits a strong, nearly monotonic upward trend across the Albertine Rift domain during the course of the 21st century. The increase averages +0.35% per year, yielding a net increase of 31% in 2090 relative to the 1990 baseline. Spatially, a strong north-south gradient present in the initial condition plot for 1990 intensifies throughout the century while values increase in magnitude overall throughout the region.

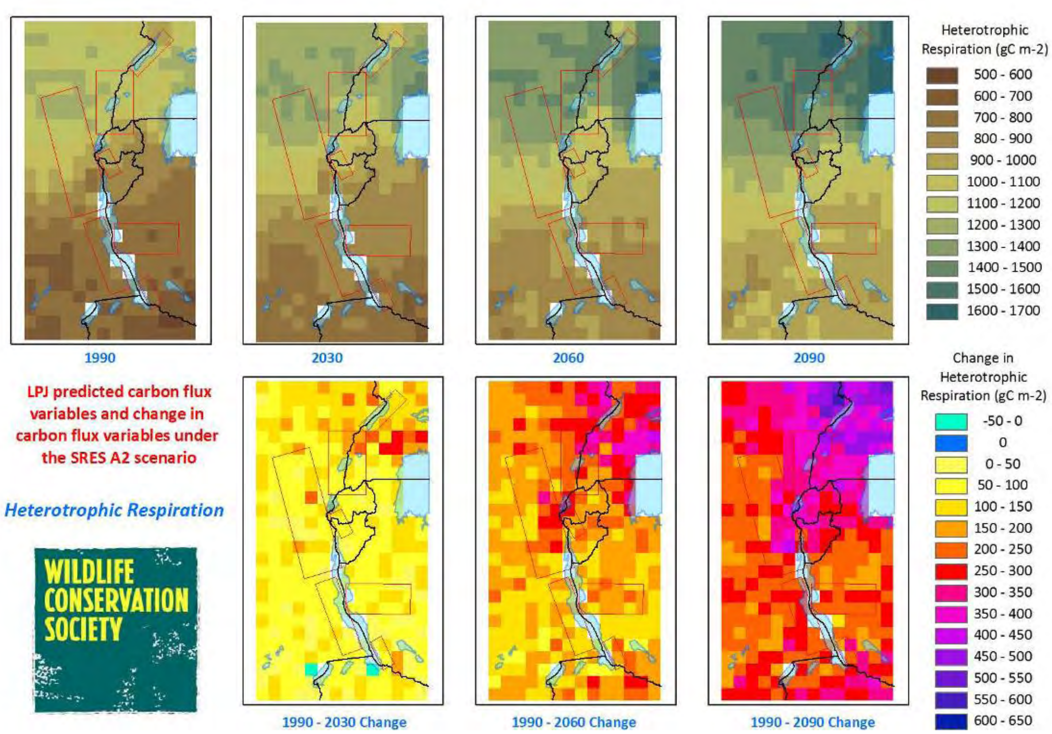

Figure 5: Annual mean Heterotrophic Respiration and change relative to 1990 historical baseline from LPJ model simulations in 2030, 2060 and 2090 under the A2 emissions scenario

Interpretation: The largest increases are found in the northern rift region, and presumably relate to concomitant increases in Net Primary Productivity and the warming and moistening climate, which collectively promote increasing biomass decay. The growing disparity between Heterotrophic Respiration with Net Primary Production is of interest, since it implies increased carbon loss to the atmosphere which has important implications for the long-term sustainability of carbon sequestration. This potentially includes projects concerned with Reduced Emissions from Deforestation and Degradation (REDD), among others, which are currently in development as a means of mitigating climate change. Together these figures indicate that climate change will bring about corresponding changes in ecosystem function – with generally higher ecosystem productivity. While this may be a benefit for biodiversity at some levels in the food chain, there may be negative impacts of these changes such as increased fire due to higher available fuel load.

Total Carbon

In the A2 model simulations mean Annual Total Carbon exhibits very little change as trends in its constituent components tend to balance one another across the Albertine Rift domain during the course of the 21st century.

Interpretation: The absence of any trend is of interest given how profoundly other landscape characteristics are projected to evolve in the same modeling simulations. Determining the significance of the carbon-related modeled parameters is somewhat outside the immediate focus of our analysis, but we include here and in the data sets as an invitation for further examination.

Crop yields

For the parameters that serve as proxy indicators for agricultural productivity, predictions for crop yields in the A2 simulations show a strong decline in mean yields for Phaseolus Beans, relatively constant yields for Maize (but these begin to decline towards the end of the century), and

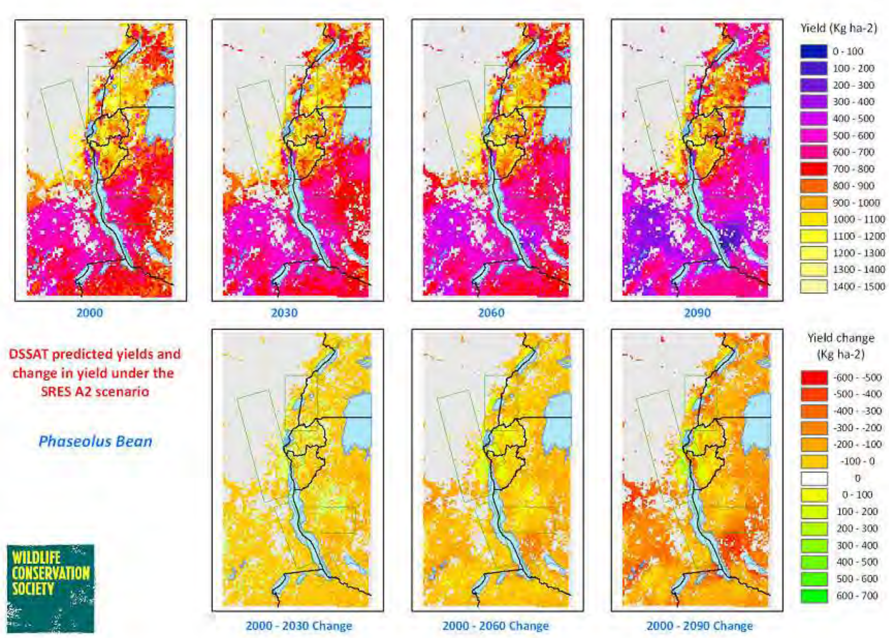

Figure 6: Potential annual yield of Phaseolus Beans and change relative to 1990 historical baseline from DSSAT model simulations in 2030, 2060 and 2090 under the A2 emissions scenario

significant increases in yield for *Brachiaria decumbens*, the indicator species for livestock. The potential distribution and spatial change patterns for Beans are presented in Figure 6. Declines are widespread, except in highland of the central rift where some gains are registered. By 2090 the southern part of the rift domain has lost most, and in some parts all, of its potential for cultivation of this crop. In contrast, the most elevated parts of the massifs of the central rift show gains.

Spatial pattern for Maize are likewise of different sign as a function of space – and also largely negative (Figure 7). Potential productivity suggests a strong elevational as well as latitudinal dependence that appears to be largely sustained over time. The central highland region of the rift is depicted to be highly productive in the present, and even more so in the future under the A2 scenario's far warmer and wetter climate at century's end. On the other hand, the densely settled agricultural lands at lower elevation in the Lake Victoria watershed east of the Albertine Rift show some of the largest early reductions in yield, by 2030, and this only intensifies thereafter.

In contrast to the two food crops above, the livestock forage crop Brachiaria exhibits a more complex pattern in its potential distributions (Figure 8). Initially, by 2030 widespread declines in yield dominate and are strongest in the southern highlands, while the central region remains largely neutral. Continued changes to climate and the environment in the model thereafter cross a threshold that greatly expands the domain and productivity of the grass.

Interpretation: These trends and patterns identify that just as floral and faunal assemblages will be forced to adapt to changing climate conditions, so too will human cropping systems and rural livelihoods. The spatial distributions are also informative in contrasting the diverse change patterns for each crop, and communicate effectively the perils of trying to generalize agricultural production by focusing on a single cultivar or environmental variable.

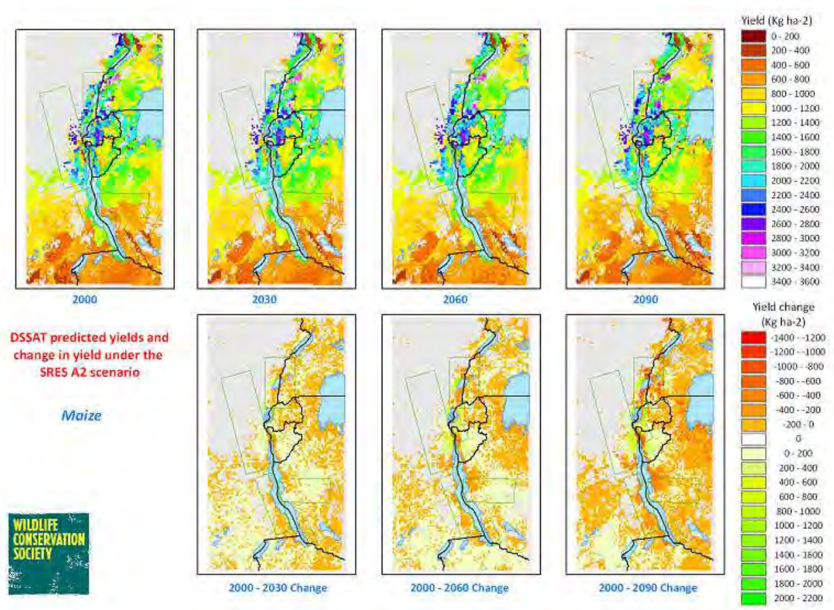

Figure 7: Potential annual yield of Phaseolus Beans and change relative to 1990 historical baseline from DSSAT model simulations in 2030, 2060 and 2090 under the A2 emissions scenario

In many instances, human adaptation could initially occur through simple *in situ* substitution of crops and livestock species more tolerant of the new climate regimes that become established. Eventually, however, climatic conditions and attendant vegetation changes may promote more substantial shifts from cultivation to livestock husbandry, and vice versa. However, by the latter half of the century, climatic conditions will be approaching levels that would seem destined to force much stronger responses yet, such as upward human migration to cooler climatic zones, and out migration from lowland regions altogether. The DSSAT modeling identifies that the central highlands of the Albertine Rift are the only beneficiary of increased productivity of all three cultivars. In this light, the diminishing agricultural potential of the Lake Victoria basin might play a significant role in conservation outcomes for the Albertine Rift and its highland havens of biodiversity The patterns imply that pressure to exploit highlands for food production will intensify, propelled by push and pull factors in a formidable combination that would seem to stand as a serious challenge to conservation.

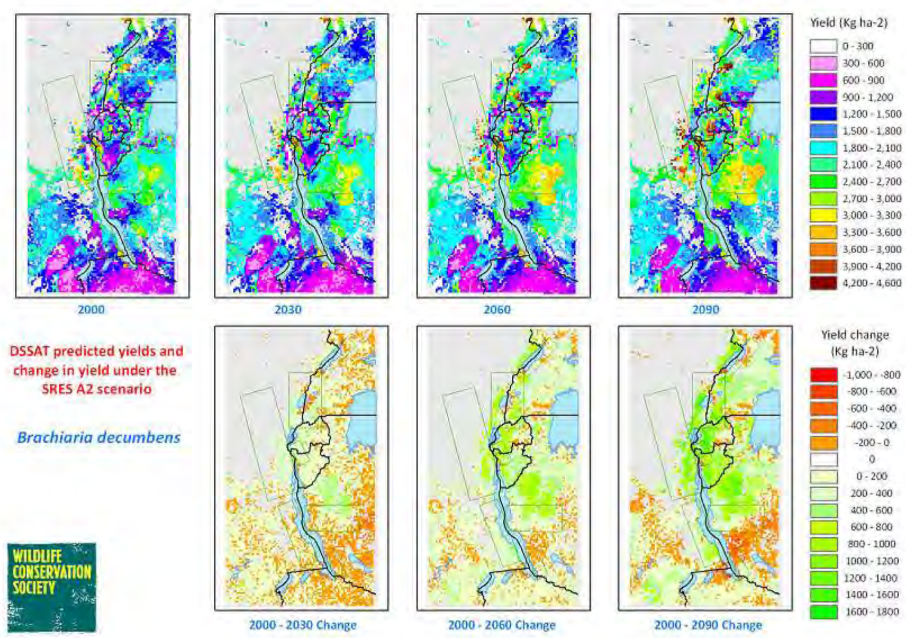

Figure 8: Potential annual yield of* Brachiaria decumbens *and change relative to 1990 historical baseline from DSSAT model simulations in 2030, 2060 and 2090 under the A2 emissions scenario

Plant Functional Type

Although not represented in the statistical breakdown in Table 1, Plant Functional Type is of particular interest for is spatial patterns, as represented for the Tropical Broadleaved Evergreen Tree class shown in Figure 9. The initial condition state, represented by 1990, shows a strong gradient from north to south of maximum to minimum coverage values, respectively. A century of change has significantly diminished this gradient by 2090, while maintaining its overall form and orientation. In particular, large gains in are experienced in the southern part of the domain, where the significantly moistened climate promotes these gains at the expense of the broadleaved raingreen class, according to the model output. This implies a significant change in forest structure, if not a complete shift in biome type across a large part of the rift domain containing some of its most important conservation areas.

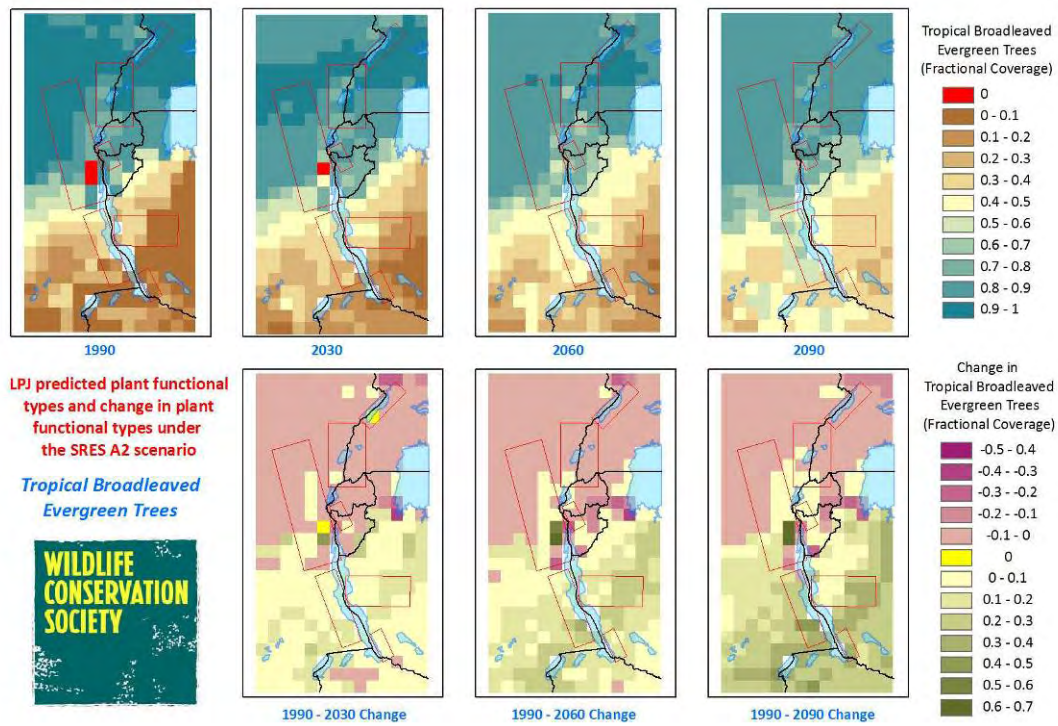

Figure 9: Fractional coverage and change relative to 1990 historical baseline of Tropical Broadleaved Evergreen Trees (Plant Functional Type trbe) from LPJ model simulations in 2030, 2060 and 2090 under the A2 emissions scenario

Fire

Among its suite of ecologically focused products, the LPJ model generates a product indicative of fire, quantified as an ecosystem function through carbon loss to the atmosphere. The most significant changes are depicted in the northern parts of the rift, where initial high values of carbon loss from fire reduce greatly under the moistening climate despite the large gains in net primary productivity. A strong trend of increase becomes evident in the Lake Tanganyika watershed region, though high values of carbon loss have not yet become apparent by 2090.

Change and resilience

One of the most striking features of the data summary in Table 1 when viewed collectively is the magnitude of the range in parameter values represented among the ~50-km scale grid cells of the project domain. Their trends indicates that the high degree of spatial variability that exists now is predicted to remain, even while baseline means shift significantly throughout the Albertine Rift. Both temperature and precipitation increase towards 2090. Temperature maxima increase at almost the same rate as minima (3.7°C compared to 3.67°C). Equally, minimum and maximum precipitation both increases by 17.6 and 19.7 mm, respectively, over the 100 year period. Maximum annual runoff increases by 36%, whereas the minimum almost doubles. Maximum and Minimum Annual Net Primary Production also increases by 20% and 30% respectively, and for Heterotrophic Respiration the same figures are 30% and 48%. Net changes in cloud cover appear to be negligible across the entire rift, as do changes in Total Carbon.

Taken together these figures indicate that climate change will bring about corresponding changes in ecosystem function – with generally higher ecosystem productivity. While this may be a benefit for biodiversity at some levels in the food chain, there may be negative impacts of these changes such as increased fire due to the higher available fuel load, and changes in vegetation assemblages.

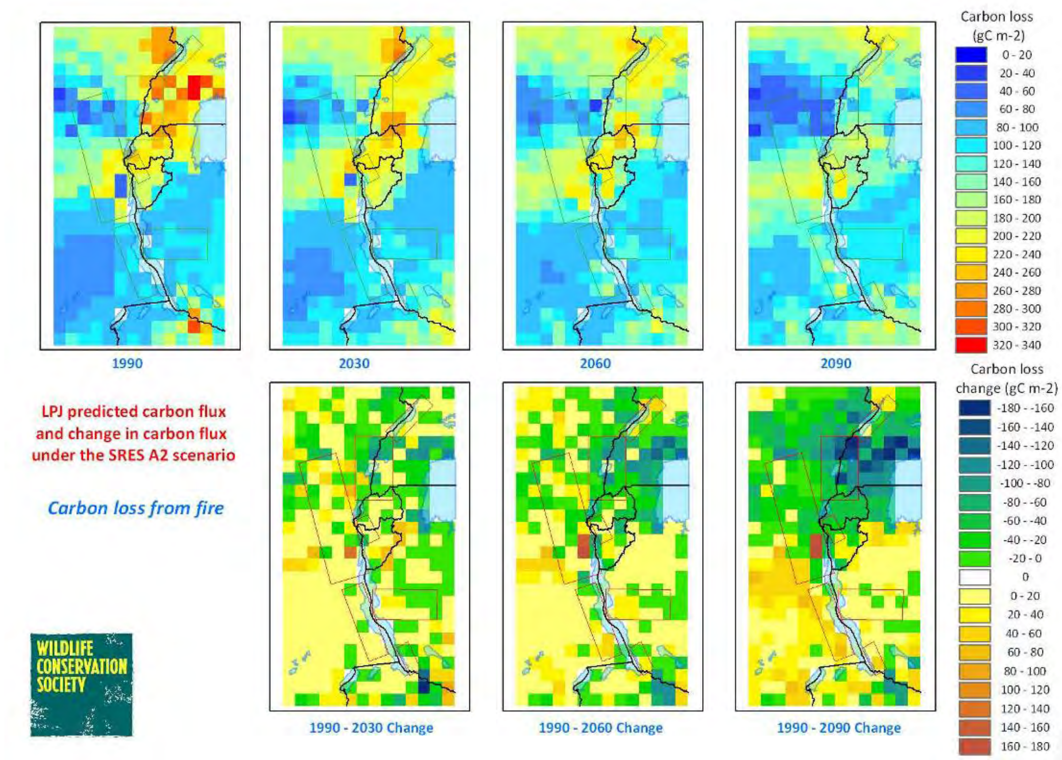

Figure 10: Predicted carbon loss from fire and change relative to 1990 historical baseline from LPJ model simulations for 2030, 2060 and 2090 under the A2 emissions scenario

3b. Conservation landscape sub-regional analyses

The synoptic perspective provided above offers generalized observations at Albertine Rift regional scale. In order to elucidate the implications of predicted climate change for biodiversity conservation at the management level, it is necessary to examine the potential impacts at a higher spatial resolution. The project therefore examined 7 sub-regional case study sites in and around the Albertine Rift selected for their recognized importance for biodiversity and conservation. The sub-regions are sized and oriented in various configurations and identified by the rectangular outlines delineated in Figure 1. The study sites are distributed along and on both sides of the rift corridor, and encapsulate a relatively complete range of elevations, biomes and climatic gradients found across the Albertine Rift.

The following section summarizes model output and key findings of predicted climate change at the landscape level for each case study sub-region. Included in the discussion is initial assessment of potential impacts upon biodiversity, though more specific assessment examining individual species and taxonomic groups will be addressed in later work. Complete bio-climatic statistical profiles and suite of modeled products for each sub-region is available for download from the project website[1].

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http://programs.wcs.org/Resources/Downloads/tabid/2801/Default.aspx

In the tabular data we have concentrated on a selection of variables with the most direct relevance for biodiversity conservation as follows: Hydrological Runoff, Net Primary Production, Heterotrophic Respiration and Total Carbon. Their relevance lies in the way these ecosystem functions interact under change to determine habitat type and resource availability. Unless otherwise indicated, the values shown are the results of spatial zonation calculations on datasets for each of the core biodiversity areas. For example, for the monthly climatic variables represented by "bar and whisker" charts, the bar indicate the mean value of all grid cells within each core biodiversity area, while the range of minimum and maximum pixel values encountered within the core area are indicated by the "whisker" line segments (these should not be interpreted conventionally as error bars).

Following the format utilized in Table 1 above, the profiles presented here show spatial summaries of predicted conditions in each of the sub-regional case study sites. The *Min* and *Max* values refer to the opposing pixel value extrema of a particular climate, ecosystem or crop yield parameter encountered within the case study domain, whereas the *Mean* is the arithmetic average of all pixel values within the delineated region.

Sub-region I: Greater Virunga Landscape

The Greater Virunga Landscape sub-region encompasses the most extreme range of landscapes in the Albertine Rift both topographically and ecologically, ranging from the relatively arid lowlands plains on the valley floor in the Queen Elizabeth National Park to the glacierized heights of the Rwenzori Mountains a short distance away. Predictions of several climatic, ecological and agricultural parameters for the sub-region are summarized in Table 1. Predicted temperature changes show the same trends and magnitudes noted throughout the rift region while precipitation change is a relatively modest 16% by 2090. On the other hand, runoff more than doubles (+118%) as vegetative uptake and evapotranspiration decline, though these changes mostly take place after mid-century.

		1990	2030	2060	2090	
Mean Monthly Temperature	*Min*	16.6	17.5	18.6	20.2	°C
	Mean	**20.4**	**21.3**	**22.5**	**24.0**	
	Max	23.9	24.7	25.9	27.5	
Annual Precipitation	*Min*	740	747	791	904	mm
	Mean	**1145**	**1153**	**1207**	**1332**	
	Max	1653	1678	1739	1864	
Runoff	*Min*	43	28	50	127	mm
	Mean	**147**	**148**	**192**	**320**	
	Max	383	432	538	660	
Net Primary Production	*Min*	1131	1228	1335	1475	$gC\ m^{-2}$
	Mean	**1286**	**1383**	**1488**	**1560**	
	Max	1404	1524	1659	1712	
Heterotrophic Respiration	*Min*	928	1002	1088	1247	$gC\ m^{-2}$
	Mean	**1091**	**1201**	**1333**	**1451**	
	Max	1220	1326	1484	1597	
Bean Yield	*Min*	1	11	73	403	$kg\ ha^{-2}$
	Mean	**995**	**969**	**950**	**870**	
	Max	1497	1443	1387	1271	
Maize Yield	*Min*	46	213	667	571	$kg\ ha^{-2}$
	Mean	**1941**	**1935**	**1908**	**1787**	
	Max	3531	3539	3402	3111	
Brachiaria Yield	*Min*	2	4	6	15	$kg\ ha^{-2}$
	Mean	**1778**	**1931**	**2194**	**2487**	
	Max	3952	4059	4286	4957	

Table 1 – Summary of modeled climate, ecosystem and crop yield parameters under the A2 emissions scenario for the Greater Virunga Landscape sub-region of the Albertine Rift

The control of surface elevation over temperature is evident in the downscaled grid cell values predicted under the A2 scenario for the year 2090 shown in Figure 11. Further ecosystem impacts are projected with increases of Net Primary Production and Heterotrophic Respiration, which increase by 21% and 33% respectively; the imbalance might be indicative of changes in carbon sequestration function. Queen Elizabeth National Park contains some of the driest areas in the landscape, and is projected to initially experience slight decreases in precipitation as temperature inexorably increases by 2060. Seasonal drought may become more severe under this combination, increasing stress to vegetation and wildlife and exacerbating fire threats. In contrast, highland regions may experience a more favorable hydrological balance as precipitation surpluses offset evaporative losses promoted by warming temperatures.

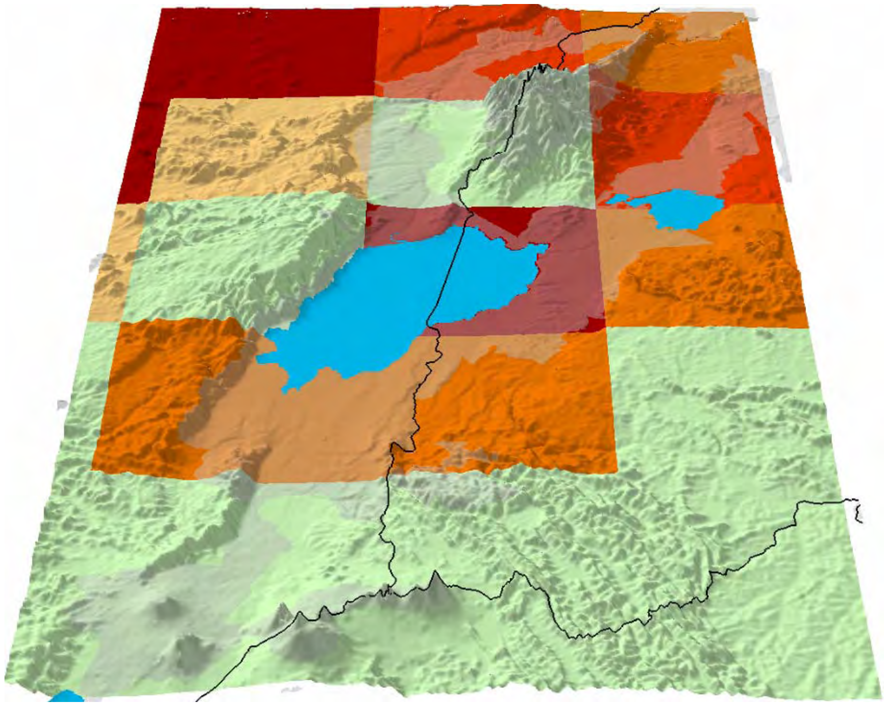


Figure 11: Three-dimensional model of the Greater Virunga Landscape viewed to the north illustrating the areas that, in 2090, will remain within the present day landscape range of temperatures (light green) and those areas that will see temperatures above the present day maximum currently found in the landscape (orange – red). Notable features are the Virunga volcanoes in the south of the scene, the Rwenzori Mountains, Lakes Edward and George, as well as the extensive and connected protected area system (light grey shading).

The Greater Virunga Landscape is an important place for people as well as wildlife, with large areas of smallholder farmlands interspersed among important protected areas. Predicted crop yields indicate that both Bean and Maize mean yields will decline only slightly initially, but then more rapidly after 2060, with net changes of -12.5% and -7% by 2090, respectively. Yields of the Brachiara forage grass will increase rapidly and significantly, reaching nearly 40% above the historic baseline by century's end. While the outcomes of such changes are uncertain, the implications of reduced agricultural yields and expansion of pastoralism are not positive for biodiversity in the region – suggesting an increased reliance on natural resource use.

Sub-region II: Nyungwe – Kibira

This cool, well-watered upland region is one of the smallest considered in this section. The model products identify the familiar intensifying warming and moistening trends through the century that proceed in relatively proportional balance (Table 2). A steepening decline in evapotranspiration mirrors an opposing rise in runoff. Large increases in Net Primary Production (32%) and Heterotrophic Respiration (37%) are registered by 2090.

		1990	2030	2060	2090	
Mean Monthly Temperature	*Min*	17.3	18.1	19.3	20.9	°C
	Mean	**19.7**	**20.6**	**21.7**	**23.3**	
	Max	22.4	23.3	24.5	26.1	
Annual Precipitation	*Min*	1019	1041	1089	1201	mm
	Mean	**1281**	**1299**	**1347**	**1454**	
	Max	1603	1617	1674	1792	
Runoff	*Min*	172	200	251	383	mm
	Mean	**317**	**352**	**408**	**536**	
	Max	618	605	638	826	
Net Primary Production	*Min*	1062	1110	1109	1246	gC m^{-2}
	Mean	**1100**	**1230**	**1315**	**1455**	
	Max	1172	1290	1398	1515	
Heterotrophic Respiration	*Min*	853	947	988	1098	gC m^{-2}
	Mean	**913**	**1006**	**1092**	**1257**	
	Max	973	1047	1185	1324	
Bean Yield	*Min*	559	557	467	280	kg ha^{-2}
	Mean	**1057**	**1063**	**1070**	**1046**	
	Max	1462	1386	1366	1332	
Maize Yield	*Min*	856	873	964	1008	kg ha^{-2}
	Mean	**1826**	**1872**	**1944**	**1990**	
	Max	2949	2866	2856	2956	
Brachiaria Yield	*Min*	416	568	902	1203	kg ha^{-2}
	Mean	**1669**	**1933**	**2262**	**2703**	
	Max	4056	4298	4577	4880	

Table 2 – Summary of modeled climate, ecosystem and crop yield parameters under the A2 emissions scenario for the Nyungwe-Kibira sub-region of the Albertine Rift

Little change in Plant Functional Type is indicated over time. Potential crop yields for Bean are quasi-stable throughout, while Maize increases by 9% through 2090. Brachiaria forage rises rapidly, with yield by 2090 rising by 62% above the 1990 baseline. According to the model output, several of these strong trends are purportedly in progress early in the assessment period, and thus at the present time, so should be detectable and verifiable through long-term field observations and monitoring.

The overall picture for this sub-region is a relatively favorable depiction of the future from a biodiversity conservation perspective. This probably relates to the high mean elevation of the landscape and significant tracts of preserved forest cover in protected areas. In the face of climate change, the biodiversity stronghold represented by Nyungwe National Park in Rwanda could be anticipated to have particularly enduring sustainability compared to many other Albertine Rift protected areas, especially those at lesser elevation.

Sub-region III: Southern Lake Tanganyika

This small landscape is the southernmost of the sub-regions considered, and features relatively strong and complex environmental change signals, especially in the LPJ model output (Table 3). These changes are indicative of the broader patterns predicted throughout the southern extent of the Albertine Rift, as described in the regional assessment in section 3b.

Temperature in the sub-region is predicted to remain within present day range throughout most of the landscape for 2030 & 2060, but mean increases of 3.4°C by 2090 push the majority of the landscape outside the present day range of temperatures. Precipitation is predicted to exceed the present day landscape maximum throughout the entire landscape in 2030, 2060 & 2090 – increasing by almost 260mm (26.5%) at 2090.

		1990	2030	2060	2090	
Mean Monthly Temperature	*Min*	18.7	19.5	20.6	22.0	°C
	Mean	**21.6**	**22.5**	**23.6**	**25.0**	
	Max	24.5	25.3	26.5	27.9	
Annual Precipitation	*Min*	893	965	1024	1153	mm
	Mean	**975**	**1045**	**1103**	**1234**	
	Max	1112	1180	1248	1385	
Runoff	*Min*	224	268	282	368	mm
	Mean	**288**	**309**	**333**	**416**	
	Max	338	376	432	532	
Net Primary Production	*Min*	804	878	941	1020	$gC\ m^{-2}$
	Mean	**835**	**913**	**1000**	**1101**	
	Max	856	936	1028	1159	
Heterotrophic Respiration	*Min*	621	748	823	927	$gC\ m^{-2}$
	Mean	**708**	**792**	**861**	**958**	
	Max	763	824	884	987	
Bean Yield	*Min*	488	388	241	88	$kg\ ha^{-2}$
	Mean	**704**	**622**	**570**	**441**	
	Max	887	735	747	684	
Maize Yield	*Min*	513	535	557	502	$kg\ ha^{-2}$
	Mean	**683**	**660**	**675**	**602**	
	Max	945	888	876	779	
Brachiaria Yield	*Min*	693	690	863	839	$kg\ ha^{-2}$
	Mean	**1380**	**1305**	**1424**	**1320**	
	Max	2216	1915	2160	1851	

Table 3 – Summary of modeled climate, ecosystem and crop yield parameters under the A2 emissions scenario for the Southern Lake Tanganyika sub-region of the Albertine Rift

Although this increase in precipitation is modest in absolute terms, the impact of such an increase is greatly amplified in a relatively (for the Albertine Rift) arid environment. The LPJ model presents a scenario spawned of these climatic trends of a major replacement of plant functional type from tropical broadleaf evergreen to raingreen forest (Figure 12). The increasing rate of change yields a net replacement of 30% by 2090. The conservation implications of such a change need to be assessed accordingly.

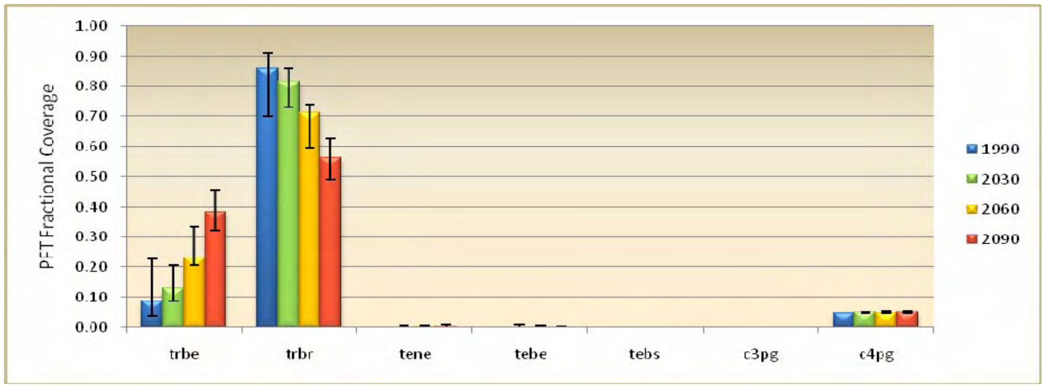


Figure 12: Plant Functional Type in the Southern Lake Tanganyika sub-region as projected for the 21st century by the LPJ vegetation model under the A2 scenario

In contrast to most other areas examined where trends in Evapotranspiration and Runoff are opposed, here they both increase simultaneously until mid-century. Intensifying runoff thereafter also increases considerably by 2090 – reaching 44% above the 1990 baseline. In this landscape, where drainage channels flow down the steep escarpment from the plateau to Lake Tanganyika, the effects of increased runoff here will be significant and might include changes in lake chemistry and siltation. The riverine forest habitat that surrounds the drainage channels is a key habitat for chimpanzees, and any destructive influence on this habitat holds high potential to have a direct negative influence on these primates.

Given the predicted increases in precipitation and Net Primary Production, and the indication that the climate is predicted to remain strongly seasonal, there is a good chance that both fire and flooding will increase under predicted climate change.
Both Bean and Maize yields decline towards 2090, by 35% and 12% respectively, while Brachiaria forage changes little. In one of Tanzania's most impoverished regions, these are ominous indicators for subsistence agriculture. Assuming increases in population density, such decreases in yield have a strong potential to result in more intense pressure on natural resources for sustenance in an area which is already under significant pressure due to forest clearance for agriculture and immigration from Democratic Republic of Congo.

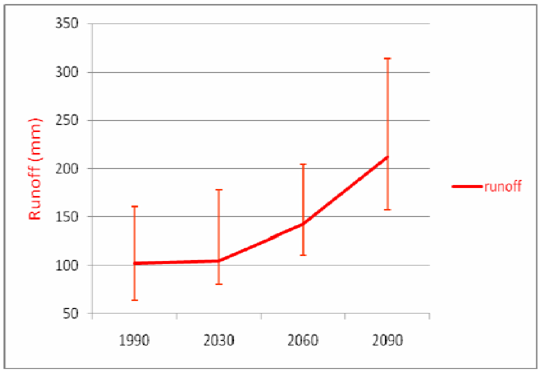
Sub-region IV: Murchison – Semliki

Under the A2 scenario the Murchison-Semliki sub-region, the northernmost of the sites examined, is projected to experience a spatially uniform temperature rise at a gradually increasing rate during the course of the 21st century (Table 4). The net thermal increase of 3.6 C translates to an upward displacement of isotherms across the landscape of approximately 660 meters, as discussed in section 3a. Annual precipitation amount increases very slowly initially, then at an accelerating rate by mid-century. The monthly rainfall proportions remain relatively unchanged except for the Dec-Feb dry season months, which show significant increases in the latter part of the century. Climatological aspects of this landscape are discussed in greater detail for Budongo and Semliki in the companion whitepaper study on climatology.

		1990	2030	2060	2090	
Mean Monthly Temperature	*Min*	21.3	22.2	23.3	24.8	°C
	Mean	**24.0**	**24.9**	**26.0**	**27.6**	
	Max	25.0	25.9	27.0	28.6	
Annual Precipitation	*Min*	919	937	1008	1141	mm
	Mean	**1130**	**1147**	**1219**	**1354**	
	Max	1433	1449	1516	1654	
Runoff	*Min*	64	81	111	158	mm
	Mean	**102**	**105**	**142**	**213**	
	Max	160	178	205	314	
Net Primary Production	*Min*	1163	1200	1338	1596	gC m^{-2}
	Mean	**1289**	**1409**	**1547**	**1667**	
	Max	1446	1537	1693	1800	
Heterotrophic Respiration	*Min*	980	1064	1203	1400	gC m^{-2}
	Mean	**1064**	**1189**	**1327**	**1482**	
	Max	1175	1318	1484	1630	
Bean Yield	*Min*	589	583	508	333	kg ha^{-2}
	Mean	**830**	**792**	**752**	**626**	
	Max	1200	1139	1071	988	
Maize Yield	*Min*	187	203	214	200	kg ha^{-2}
	Mean	**1063**	**1032**	**1005**	**921**	
	Max	2966	2932	2803	2717	
Brachiaria Yield	*Min*	66	86	97	98	kg ha^{-2}
	Mean	**1637**	**1613**	**1732**	**1714**	
	Max	3540	3720	3973	4166	

Table 4 – Summary of modeled climate, ecosystem and crop yield parameters under the A2 emissions scenario for the Murchison-Semliki sub-region of the Albertine Rift

Across the sub-region Net Primary Production responds with a steep monotonic increase of up to 24% in parts of Murchison Falls National Park and Budongo Forest Reserve. The model output suggests that this is already underway at the present time, so an objective for monitoring should be to verify and quantify this trend. The combination of increased hydrological uptake by plants and evaporative loss implied by the warming climate balance the upward trend in rainfall until mid-century, when rainfall increasingly dominates, causing marked increases in runoff (Figure 13). Fire is initially a high threat in this landscape, but the increased precipitation and runoff begin to diminish its potential towards the end of the century.



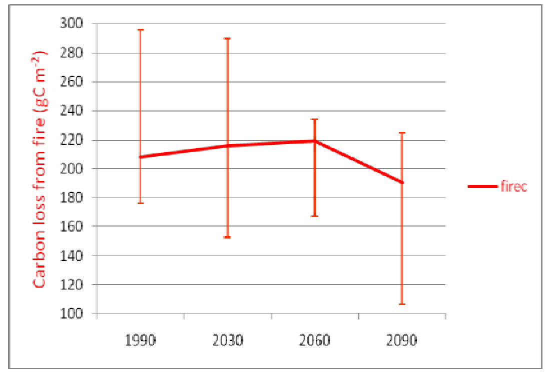


Figure 13: Predicted 21st century annual trends for runoff (left), in mm of water, and carbon loss from fire (right), in grams of carbon per square meter, derived from LPJ vegetation modeling of the Murchison-Semliki sub-region

From this information it can be inferred that Lake Albert and other water bodies might experience significant water level changes, initially negative then reversing to positive later on, along with increasing seasonal and inter-annual variability. Given the high relief topography of the landscape, there is a strong possibility that runoff increases will also intensify erosion and instability on the rift valley walls, especially the steep Blue Mountain escarpment overlooking Lake Albert from the west and a higher risk of flooding of the lowland valley floor areas in the north and south of the landscape. Increases in vegetation biomass and greater dry season aridity in the near-term yield slight increases in carbon loss from fire through mid-century, until rising precipitation levels year-round initiate a rapid decline.

Both Bean and Maize mean yields decrease consistently from the present day to 2090, by 25% & 13% respectively, while there is a slight increase in the pasture grass Brachiaria of 4%. This might indicate some tendency to shift agricultural practice towards livestock. The changing environmental parameters are projected to have a relatively minor impact on plant functional type proportions across the sub-region during the 21st century (Figure 14). Approximately 5% coverage is gained in tropical broadleaf raingreen vegetation at the expense of tropical broadleaf evergreen.

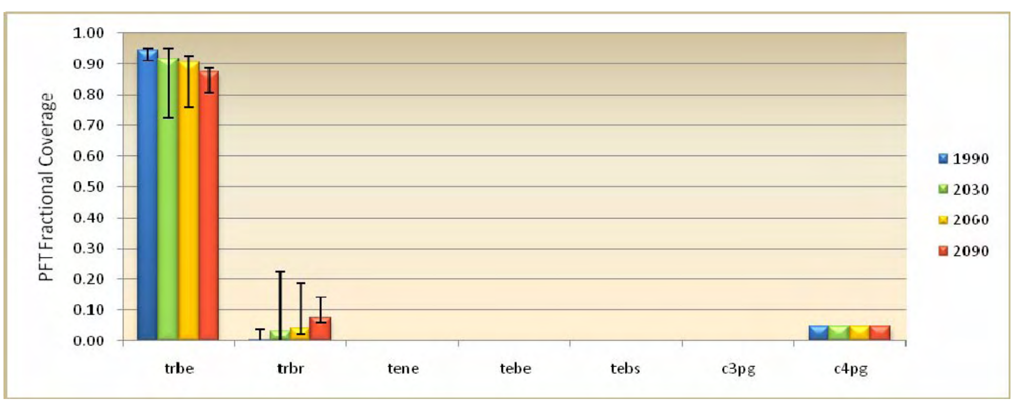


Figure 14: Plant Functional Type in the Murchison-Budongo sub-region as projected for the 21st century by the LPJ vegetation model under the A2 scenario

Sub-region V: Maiko – Itombwe

The Maiko-Itombwe core area is the largest of the sub-regions studied, and as such contains large tracts of both highlands and lowland habitat, the latter extending into the Congo rainforest. Temperature trends are virtually identical to the region as a whole, with a net mean increase of 3.6°C in 2090 (Table 5). Of note in this regard is that station observations at Lwiro in Congo DRC show an increase of 2°C over the past 60 years already, though the reliability of the observations cannot be verified. The predicted increases in mean precipitation (180mm by 2090) are small enough to ensure levels remain within the present day landscape range for the majority of the landscape in 2030, 2060 & 2090.

		1990	2030	2060	2090	
Mean Monthly Temperature	*Min*	15.1	16.0	17.1	18.7	°C
	Mean	**22.1**	**23.0**	**24.1**	**25.7**	
	Max	24.9	25.8	27.0	28.6	
Annual Precipitation	*Min*	736	750	781	910	mm
	Mean	**1351**	**1371**	**1419**	**1534**	
	Max	2044	2070	2130	2250	
Runoff	*Min*	149	158	226	356	mm
	Mean	**320**	**354**	**407**	**539**	
	Max	723	760	871	986	
Net Primary Production	*Min*	812	890	1030	1169	gC m^{-2}
	Mean	**1189**	**1275**	**1374**	**1446**	
	Max	1353	1431	1501	1586	
Heterotrophic Respiration	*Min*	739	840	942	1022	gC m^{-2}
	Mean	**1040**	**1126**	**1226**	**1310**	
	Max	1259	1350	1435	1517	
Bean Yield	*Min*	253	389	496	491	kg ha^{-2}
	Mean	**974**	**960**	**950**	**922**	
	Max	1414	1350	1323	1276	
Maize Yield	*Min*	118	312	597	701	kg ha^{-2}
	Mean	**1647**	**1680**	**1705**	**1711**	
	Max	2972	2908	2909	2818	
Brachiaria Yield	*Min*	66	102	209	459	kg ha^{-2}
	Mean	**2047**	**2208**	**2449**	**2755**	
	Max	4106	4328	4518	4722	

Table 5 – Summary of modeled climate, ecosystem and crop yield parameters under the A2 emissions scenario for the Maiko-Itombwe sub-region of the Albertine Rift

Slightly increased desiccation in the landscape is reasonable to expect given the above conditions of increasing temperatures, but relatively stable precipitation. However, the fact that Net Primary Productivity increases by almost 22% by 2090 while evapotranspiration falls at a relatively rapid and sustained rate indicates that precipitation could be held in the system longer and released more slowly through runoff. In this case, the impact of the June-August dry season may be significantly reduced.

Although mean Bean yield drops slightly (5%), both maize and Brachiaria yields increase, by 4% and 35% respectively. This follows the broader pattern of proportionally more lands becoming favorable to livestock over cultivation.

Sub-region VI: Mahale Corridors

The compound effect of changes indicated for the Mahale Corridors suggests that by the latter half of the 21st century, sustained climatic changes of warming and moistening will promote important ecological changes with implications to conservation.

Mahale is located far enough south in the Albertine Rift to experience the marked seasonal asymmetry in precipitation and cloud cover changes described in the region wide assessment above. The increase in the peak rainfall period in Nov-Dec occurs as the April peak remains almost unchanged, though diminished in a relative sense given the overall increase in annual precipitation (Table 6). As described in the companion study on climatology, a pattern relatively consistent with this trend has been observed over the past 20 years at Mahale National Park (Seimon and Picton Phillipps 2009).

		1990	2030	2060	2090	
Mean Monthly Temperature	*Min*	20.9	2.7	22.9	24.4	°C
	Mean	**22.4**	**23.2**	**24.4**	**25.9**	
	Max	23.9	24.8	25.9	27.4	
Annual Precipitation	*Min*	765	824	877	991	mm
	Mean	**1074**	**1124**	**1172**	**1290**	
	Max	1224	1268	1311	1425	
Runoff	*Min*	123	147	189	271	mm
	Mean	**272**	**288**	**319**	**419**	
	Max	346	340	380	493	
Net Primary Production	*Min*	808	892	962	1049	$gC\ m^{-2}$
	Mean	**856**	**941**	**1019**	**1088**	
	Max	895	989	1109	1165	
Heterotrophic Respiration	*Min*	690	775	850	939	$gC\ m^{-2}$
	Mean	**748**	**836**	**912**	**983**	
	Max	789	876	984	1021	
Bean Yield	*Min*	494	510	463	319	$kg\ ha^{-2}$
	Mean	**705**	**662**	**628**	**514**	
	Max	901	790	734	656	
Maize Yield	*Min*	551	589	602	549	$kg\ ha^{-2}$
	Mean	**941**	**973**	**962**	**851**	
	Max	1408	1421	1407	1294	
Brachiaria Yield	*Min*	643	643	761	790	$kg\ ha^{-2}$
	Mean	**1880**	**1974**	**2164**	**2156**	
	Max	3300	3329	3508	3532	

Table 6 – Summary of modeled climate, ecosystem and crop yield parameters under the A2 emissions scenario for the Mahale Corridors sub-region of the Albertine Rift

The dry season at Mahale is one of the longest experienced in the Albertine Rift and is relatively cloud free. Consequently, any increase in aridity under hotter conditions during the dry seasons might increase the frequency and intensity of fire throughout the landscape beyond present levels, and this is indicated by modest increases in Carbon Loss From Fire. This reverses over the latter period when precipitation increases are indicated for the the dry season months.

Trends in Plant Functional Type under the A2 scenario suggest a significant vegetative transition in rainforest type to be already in progress that will tail off in the latter part of the century. The LPJ model output projects a net gain of about 20% in regional coverage of tropical broadleaf evergreen vegetation (trbe) at the expense of a comparable fraction of tropical broadleaf raingreen vegetation (trbr); a small fraction of C4 grassland also present in the landscape is predicted to remain unchanged (Figure 15). An objective for research and monitoring should be to verify the existence of this rainforest-type transition, and understand its potential impacts upon biodiversity.

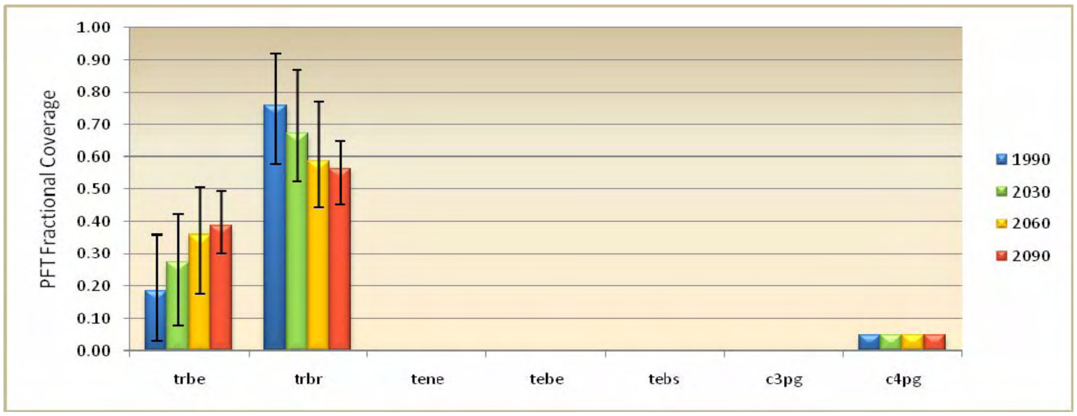


Figure 15: Plant Functional Type in the Mahale Corridors sub-region as projected for the 21st century by the LPJ vegetation model under the A2 scenario

The increasingly warm and wet climate results in large magnitude increases in Net Primary Production averaging +0.27% per year throughout the century from the 1990 baseline. Heterotrophic Respiration increases even more rapidly, averaging +0.31% per year throughout the century from the 1990 baseline. This might be an indication of diminishing carbon sequestration function of the landscape.

Not shown in the table is the Annual Evapotranspiration, which after initial rises falls steeply from 2060-2090. This might reflect factors such as greater stomatal closure of leafy vegetation as the climate becomes intensely warm and wet relative to the present, along with the building super-abundance of atmospheric CO_2. As a consequence, and in combination with the significant rainfall increase, Annual Runoff exhibits a rapidly steepening increase in the latter half of the century, raising the potential for floods and short-period lake level fluctuations and possible higher overall lake stands despite the large increase in evaporation resulting from the significantly warmed climate.

Changes in modeled cultivar production are relatively small through mid century but both Bean and Maize yields decline towards 2090, by 27% and 9% respectively, while in contrast to much of the broader region Brachiaria forage increases only slightly. In one of Tanzania's most impoverished regions, this is not a good sign if it is indicative of production trends for alimentary resources. Assuming increases in population density, overall decreases in production could be inferred to promote food shortages leading to out-migration or more intense pressure on natural resources for sustenance – or possibly a mixture of the two.

Sub-region VII: Marungu – Kabobo

Similar to the predictions discussed for nearby Mahale and Southern Lake Tanganyika sub-regions, the compound effect of changes indicated for the Marungu-Kabobo sub-region suggests that by the latter half of the 21st century, sustained climatic changes of warming and moistening will promote important ecological changes of consequence to biodiversity and conservation.

Temperature is predicted to exceed the present day range throughout most of the landscape in 2030, 2060 & 2090, increasing by 3.5°C by 2090 (Table 7). Precipitation is predicted to remain within the present day landscape range for the majority of the landscape in 2030, but exceeds the present day landscape maximum in most of the landscape in 2060 & 2090 – increasing by 94mm (8%) and 204mm (19%) in 2060 & 2090 respectively.

		1990	2030	2060	2090	
Mean Monthly Temperature	*Min*	19.7	20.5	21.7	23.1	°C
	Mean	**22.1**	**23.0**	**24.1**	**25.6**	
	Max	23.7	24.6	25.7	27.3	
Annual Precipitation	*Min*	828	883	941	1049	mm
	Mean	**1076**	**1122**	**1170**	**1280**	
	Max	1341	1379	1419	1528	
Runoff	*Min*	138	177	244	347	mm
	Mean	**225**	**274**	**321**	**431**	
	Max	368	401	450	545	
Net Primary Production	*Min*	817	884	961	1045	gC m^{-2}
	Mean	**853**	**935**	**1014**	**1138**	
	Max	916	988	1081	1201	
Heterotrophic Respiration	*Min*	712	782	867	943	gC m^{-2}
	Mean	**760**	**833**	**913**	**1007**	
	Max	812	873	975	1041	
Bean Yield	*Min*	496	477	465	322	kg ha^{-2}
	Mean	**660**	**615**	**599**	**543**	
	Max	852	775	793	801	
Maize Yield	*Min*	463	460	516	467	kg ha^{-2}
	Mean	**1081**	**1047**	**1016**	**889**	
	Max	1952	1906	1856	1831	
Brachiaria Yield	*Min*	644	693	791	955	kg ha^{-2}
	Mean	**1680**	**1696**	**1896**	**2020**	
	Max	3244	3262	3354	3598	

Table 8 –Summary of modeled climate, ecosystem and crop yield parameters under the A2 emissions scenario for the Marungu-Kabobo sub-region of the Albertine Rift

Hydrological Runoff also exceeds present day landscape maximum values across most of the landscape - generally within the 0 - 10% range in the northern parts, but increasing to a maximum of 50% above the present day landscape maximum to the southern end. Net Primary Production and Heterotrophic Respiration also increase above the present day landscape maximum - reaching 32% and 30% above present day levels respectively.

The possibility of more severe and widespread fire must also be considered as high risk - given the increases in Net Primary Productivity and increased desiccation. An alternative view is that the risk of fire will be reduced due to the wetter conditions in the dry season created by increased Net Primary Production slowing down the hydrological cycle in the landscape, ensuring that more water is retained for a longer period of time in the dry season.

As with the nearby Southern Tanganyika and Mahale Corridor landscapes, the LPJ model indicates the likelihood of a significant change in Plant Functional Type in progress throughout the course of the 21st century in the Marungu-Kabobo sub-region (Figure 16). The net replacement of tropical broadleaf evergreen to raingreen forest is about 27% by 2090.

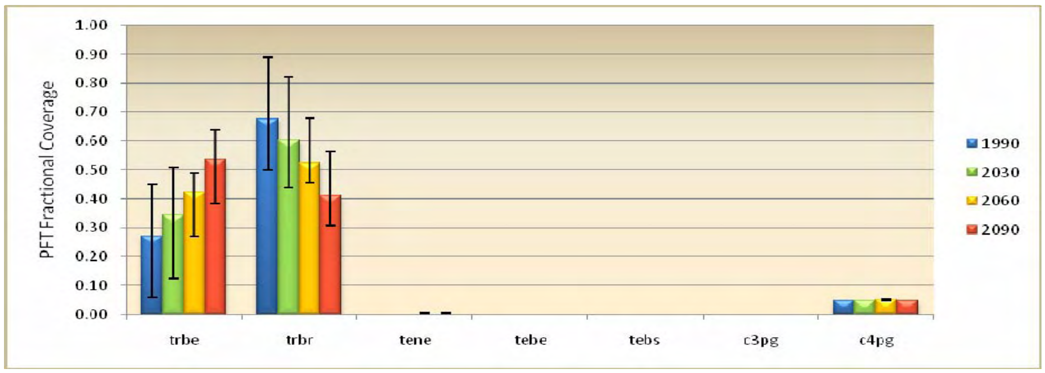


***Figure 16: Plant Functional Type in the Marungu-Kabobo sub-region as projected for the 21st century by the LPJ vegetation model under the A2 scenario*.**

Both Bean and Maize yields decrease towards 2090 by 17% and 18% respectively. There is an increase in Brachiaria yields of 20% by 2090, indicating that agricultural systems may either switch to pastoral under predicted climate change, or will require more land to produce food for the population – which is assumed to increase towards 2090.

4. DISCUSSION

Evaluation of climate change impacts upon Albertine Rift biodiversity based upon the model predictions generated by the Climate Assessment project has two distinct aspects: what the data shows, and how to interpret what the data shows. In this section we offer a perspective on how conservation interests might best consider and utilize the information presented in the Modeling Results section above and the assorted model products.

4a. Representation and usefulness of modeling products

Climate model output offers a first step towards predicting how climate change will influence biodiversity, but as demonstrated in this study it requires additional steps to make it meaningful for conservation management through generation of products more relevant to ecological systems. The utility of using GCM output to generate secondary sets of parameters for investigating the potential impacts of climate change on biodiversity is readily apparent. For example, from the downscaled IPCC climate predictions under different scenarios it is possible to quantify precipitation change for a given location. That information is inherently useful, but applying the LPJ algorithms develops this information further by estimating the amount of available water at that location, the fraction returned to the atmosphere through evapotranspiration, and the residual amount likely to become runoff. In terms of biodiversity conservation, this extended information is highly informative in determining factors influenced by climate change such as suitable species' habitat distribution, carbon budgets and sequestration, and disturbance processes such as fire.

4b. Recommendations on appropriate use

The climate, crop and ecosystem modeling conducted during this project have yielded a wealth of potentially useful information with wide applicability throughout the Albertine Rift region. Taken collectively, they offer a multifaceted view to the future of potential climate and ecosystem conditions at key biodiversity sites throughout the rift valley. However, in evaluating these products it is critically important to continually recall the many caveats associated with the use of this information, among which are that:

- GCM accuracy and representation are uncertain and of coarse resolution
- GCMs are far from consistent in depicting common climatic outcomes
- Emissions scenarios are mere guesses of unknowable future anthropogenic forcings
- Non-greenhouse gas climate forcings, especially those related to anthropogenic land cover modification, are significantly underrepresented in GCMs (e.g. Paeth et al 2009)

Of particular importance, not considered at all in this analysis is the potential influence on wildlife and humanity of climatically sensitive pests and pathogens, many of which are highly likely to respond to climate change and which may ultimately be among the strongest factors driving species response, including that of humans. The WCS Global Health Program has highlighted twelve pathogenic diseases linking wildlife and humans with recognized characteristics suggesting them to be subject to climate change influence: most are known to occur inside or near to the Albertine Rift region and include Ebola, Rift Valley Fever and Trypanosomiasis, “sleeping sickness” spread by the tsetse fly (WCS GHP 2008)

How the information produced by the WCS Climate Assessment project might best be utilized by interests concerned with Albertine Rift conservation management and planning is thus something of an open question. Whereas generation of model products is a largely technical and mechanistic undertaking, making this information useful for practical applications such as conservation planning requires some degree of subjective evaluation and interpretation by informed analysts. For certain applications it may be sufficient to utilize model output directly. For example, to understand prospects for continued deglaciation of the Rwenzori Mountains though the 21st century it would be sufficient to use the atmospheric variables of temperature, precipitation and cloud cover from the downscaled global climate model output, since these can be directly input into a glacial mass balance model developed for the Rwenzori from historic data. In contrast, for most environmental and virtually all conservation applications, a nuanced approach heavily reliant on local knowledge of area biodiversity, ecological systems and the human component of the landscape would seem to be almost obligatory.

Therefore, no matter how clear and compelling the model products presented in this report may seem as representations of the future, for now they must instead only be considered as guides towards visualizing and understanding how climate change will affect species and ecosystems across the Albertine Rift. The maps and figures presented here should not be considered as windows looking out into the future: rather, they are tools to help us better anticipate and understand what the future might look like.

The approach espoused here for conservation applications is to use the generated model products as guidance rather than gospel, where future projections of a suite of parameters can serve as inputs to conceptual models of possible future outcomes that will play out over time. Since it is practically impossible to accurately predict outcomes of a multitude of interacting factors, forcings and parameters over time for any given context, we recommend using modeled products and predictions presented here as heuristic tools for building scenarios of possible courses of action aimed at achieving the conservation outcomes desired.

4c. Albertine Rift protected areas and climate change

From a macro-scale perspective, the information generated by this project suggests that the mountainous highland regions of the Albertine Rift flanking the region's great lakes collectively stand as the best-hope refuge for sustaining biodiverse ecosystems with a strong semblance to present form over the long term. This assessment can be based on simple recognition that the mountainous uplands of the Albertine Rift contains the greatest topographic relief and elevated terrain, though the environmental modeling amply reaffirms this inference and allows it to be quantified. That the Albertine Rift contains such a geographic endowment, which is without parallel in scale and extent throughout Tropical Africa, also means that this region has the potential to be a stalwart haven for biodiversity in the face of anthropogenic climate change – provided that other more traditional conservation threats can be adequately constrained and controlled. On the other hand, the upward taper of topography also means that range contractions of biota will be omnipresent, with increasing pressure for ecological resources and services both among species and by humans likewise coerced to move to higher elevations to sustain livelihoods and track favorable living conditions.

This inference alone suggests that the highest priority for conservation from a climate change perspective in the Albertine Rift should be to safeguard with protected area status as many high elevation and mountainous habitats as possible. Existing protected highland forests such as at Nyungwe hold high potential to serve as biodiversity refugia over the long-term. A logical corollary priority would be to maintain or otherwise reestablish ecological corridor linkages interconnecting the various ranges, massifs and volcanoes. Regrettably, protected areas where the major part of the habitat occupies low elevations appear to be faced with a particularly dire predicament; this includes some very important parks such as Semliki and Queen Elizabeth National Park, both in Uganda. Species with high adaptive capacities resident in these landscapes might be able to persevere through the sweltering epoch to come, but many others, possibly including much of the human population in neighboring lands, might eventually be forced to migrate towards cooler, higher climes.

The magnitude of overall climatic and ecological change by century's end appears to be greatest in the southern parts of the rift domain, from Mahale through southern Lake Tanganyika where possible enrichment and expansion of the region's rainforests could be viewed as a largely beneficial consequence of climate change. It is sobering to note, however, that just a few more degrees of latitudes to the south is transition zone where the GCM multi-model consensus depicts an abrupt hydroclimatological shift from major moistening to major drying by the end of the century (Figure 17). Relatively small spatial displacements from a modeling perspective could yield therefore vastly different climatic outcomes for this part of the Albertine Rift. It would be informative to conduct a diagnosis of individual GCM and multi-model consensus characterizations of this transition zone in terms of geographic placement and intensity of the gradient, and then repeat this analysis for subsequent IPCC modeling cycles.

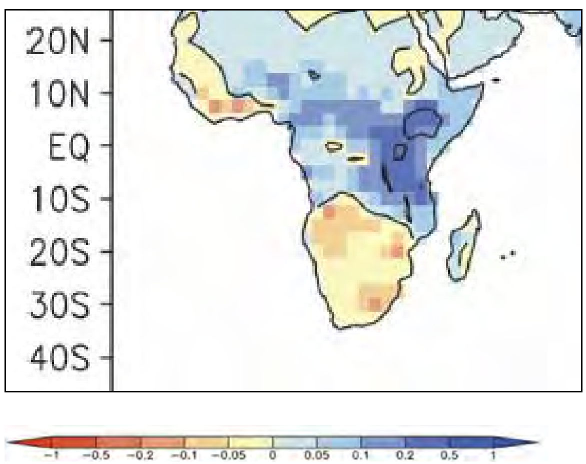


Figure 17: Multi-model GCM ensemble plot showing change in annual mean runoff for the future in 2100 versus the present. Units are in mm/day according to the scale provided. Excerpted from figure 5 in Nohara et al., Journal of Hydroclimatology 2006, p. 1083.

Even more difficult to anticipate, but potentially an even greater challenge to Albertine Rift conservation than environmental changes, are the indirect threats that will arise from human response to climate change.

4d. How results can inform conservation planning

The most compelling model results inviting boldest management decisions and actions are generally those shown for later in the century. Yet it must be remembered that projections further out in time are also the most questionable, and, if an optimistic viewpoint is adopted, such projected changes also have the greatest potential to be overridden or ameliorated by strong global policy intervention on emissions in the intervening period, as suggested in the more moderate SRES A1B and B1 scenarios. In contrast, change signals that are apparent early in the model timeline are typically of relatively small magnitude but might identify real greenhouse-gas forced atmospheric responses either imminent or already playing out, thus offering much more realistic targets for diagnosis, through monitoring, and proactive control over outcomes, through adaptive management.

In this light, the large magnitude changes that develop over the longer time periods in the model simulations might be most informative for their role as indicators of how more modest signals of a relatively benign nature seen earlier may grow into profound conservation challenges over time. Sites where long-term ecological research has been paired with climate monitoring offer some of the best opportunities to develop and explore a range of climate change scenario, with real-time monitoring data available for use as inputs and to compare with modeled scenarios.

Projections verifying several decades or more in the future should be considered more as informed speculations than explicit forecasts. At such time scales, a conceptual approach utilized by weather forecasters might be usefully applied, which is to study how model predictions themselves change as a function of time (*d*Prog/*d*t, or change in prognosis over change in time). The IPCC assessment process is iterative, with full suites of modeling performed on a 5 year timetable, enabling regular comparison and trend detection among the models themselves. Modeling studies for the forthcoming Fifth Assessment Report will soon be in process, and will be run on data sets that are now 5 more years into the future than those of the Fourth Assessment Report. The newer forecasts would not only be likely to possess greater accuracy – advances in computing and data assimilation are of course partially responsible too – but additionally informative for the contrast they bring relative to previous predictions.

4e. Future Work and Research Priorities

This project's goals of modeling and assessing the impacts of climate change upon biodiversity have been handicapped by severe observational data deficits, both in the form of poor climate monitoring data in terms of both quality and quantity, and the absence of biodiversity monitoring tailored to detection of climate change impacts. Critically needed are research grade *in situ* observations sustained over time to serve as baselines for assessing change and trend behavior, and for incorporation into increasingly sophisticated climate and landscape models. In addition, while there has been a recent expansion of cooperative, network-based studies examining climate change across the globe (e.g. RAINFOR, GLORIA, TEAM), sites in the Albertine Rift and in tropical Africa in general, are still underrepresented despite the region's rich biodiversity and important role in providing ecosystem services. Systematic monitoring of taxa with known sensitivity to climatic perturbation in the Albertine Rift region will greatly increase our ability to guide conservation decision-making about potential corridors for connectivity of wildlife and plant populations, access to grazing for domestic stock or wildlife, the proximity of or expansion of agricultural crops and land degradation affects, and examining adequate park boundaries and buffer zones.

Detailed diagnostic data on climate and key indicator species are critical for understanding adaptive scenarios and identifying immediate interventions. WCS has therefore set as a goal for forthcoming work the establishment of a long-term, joint climate and ecological monitoring network across the protected areas of the Albertine Rift that will effectively diagnose patterns and impacts of climate changes, and inform climate change adaptation planning well into the future. The network will also assist in identifying critical corridors that will need to be conserved to allow migration with climate change, and some of the vertebrate and plant species that may be most susceptible to this change.

Specific objective for this work include: Climate monitoring -- systematize and professionalize climate data collection in Albertine Rift protected areas by establishing a long-term, scientific-quality climate monitoring network designed to detect changes in climate; Vegetation monitoring -- establish long-term vegetation monitoring sites designed for detection and quantification of climate change impacts, including the influence of intensifying CO_2. fertilization on growth rates; Species response monitoring -- establish long-term faunal monitoring of vertebrate species with recognized susceptibilities to climatic perturbation; Assessment of Corridors -- assess the effectiveness of current and proposed wildlife corridors between protected areas to allow for adaptation to climate change.

In addition, efforts should continue to consolidate and analyze climatological information throughout the Albertine Rift region to build the base of understanding and baseline reference for assessing climate change. A priority is to combine high temporal resolution climatological analysis with phenological data on flora and fauna.

Finally, it would be an interesting and worthwhile exercise to repeat the environmental modeling of the Albertine Rift performed for the present study once the new IPCC GCM output becomes available to examine how predictions themselves are evolving for the 2030, 2060 and 2090 benchmark years assessed. This is the approach suggested above for tracking the steep rainfall gradient currently, but uncertainly, predicted to become established just south of the Albertine Rift over the course of the 21st century.

5. REFERENCES

IPCC 2007: Climate Change 2007: The Physical Science Basis Summary for Policymakers, Intergovernmental Panel on Climate Change.
http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

Nohara, D., A. Kitoh, M. Hosaka, and T. Oki, 2006: Impact of Climate Change on River Discharge Projected by Multimodel Ensemble. *J. Hydrometeorology.*, **7**, 1076–1089.

Plumptre, A.J., Behangana, M., Ndomba, E., Davenport, T., Kahindo, C., Kityo, R. Ssegawa, P., Eilu, G., Nkuutu, D. and Owiunji, I., 2003: The Biodiversity of the Albertine Rift. *Albertine Rift Technical Reports* No. 3, 107 pp. Available at:
http://programs.wcs.org/albertine/Publications/AlbertineRiftTechnicalReportsSeries/tabid/2531/Default.aspx

Plumptre, A.J., T.R.B. Davenport, M. Behangana, R. Kityo, G. Eilu, P. Ssegawa, C. Ewango, D. Meirte, C. Kahindo, M. Herremans, J. Kerbis Peterhans, J. D. Pilgrim, M. Wilson, M. Languy and D. Moyer, 2007: The biodiversity of the Albertine Rift. *Biological Conservation*, 134,178-194

Seimon, A. and G. Picton Phillipps, 2009: Climatological Assessment of the Albertine Rift for Conservation Applications. WCS Albertine Rift Climate Assessment, whitepaper report no. 1.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J., Levis, S. Lucht, W., Sykes, M., Thonicke, K. and Venevsky, S. (2003) *Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Vegetation Model.* Global Change Biology 9: 161 - 185

Thornton, P.K. 2009: Climate Model Data Downscaling, and Crop Model Simulation, unpublished consultant report available at
http://programs.wcs.org/albertineclimate/Docustore/tabid/428/Default.aspx?Command=Core_Download&EntryId=3938

WCS-GHP, 2008: The Deadly Dozen. Wildlife Conservation Society Global Health Program; see
http://www.wcs.org/new-and-noteworthy/deadly-dozen.aspx

Annex 1 – Data Analysis Methods

Step 1: Global Climate Model Data Acquisition and Preprocessing

The core datasets that underpin the entire data analysis component are the outputs from GCMs developed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC 2007). Gridded output from climate simulations is available for download from the Climate Model Intercomparison Project phase 3 (CMIP3) multi-model database (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). Data from a number of climate models run by different national meteorological organizations and for a wide range of climate variables under different emissions scenarios are available.

In accordance with current best practice for analyzing the outputs of climate modeling exercises, we used a multi-model ensemble comprised of data from 11 runs of 7 different climate models. Listed by their code names and countries that developed them, these models are the *bccr-bcm2.0* (Norway), *ncar-ccsm* (USA), *csiro-mk3.5* (Australia), *miroc3.2 hires* (Japan) and *miroc 3.2 medres* (Japan), *echam5* (Germany) and *hadcm3* (Great Britain). Complete documentation for each of these models is available from CMIP3 at:
http://www.pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

Model	Run	Approximate resolution at equator (km)	Total Cloud Fraction	Precipitation	Surface Air Temperature	Maximum Daily Air Surface Temperature	Minimum Daily Air Surface Temperature
Bccr-bcm2.0 (Norway)	1	313		X	X	X	X
ncar-ccsm3 (US)	3	157	X	X	X		
	5		X	X	X		
	7		X	X	X		
	9		X	X	X	X	X
csiro-mk3.5 (Australia)	1	209	X	X	X	X	X
miroc3.2 (hires) (Japan)	1	125	X	X	X	X	X
miroc3.2 (medres) (Japan)	2	313	X	X	X	X	X
	3		X	X	X	X	X
hadCM3 (GB)	1	157	X	X	X		
Echam-5 (Germany)	3	209	X	X	X		

Table 1: Summary of Global Climate Models and the parameters utilized in the present study

Due to the fact that the results of the model predictions indicate what the value of future climatic variables will be, in order to gain an appreciation of the magnitude of change this represents, it is also necessary to have an indication of present day climate. As these are specific to each model run, it is important that climate change is calculated using the correct dataset for each model run. These values were obtained from the 20C3m model results for each model run that we used, which provides information for the present day.

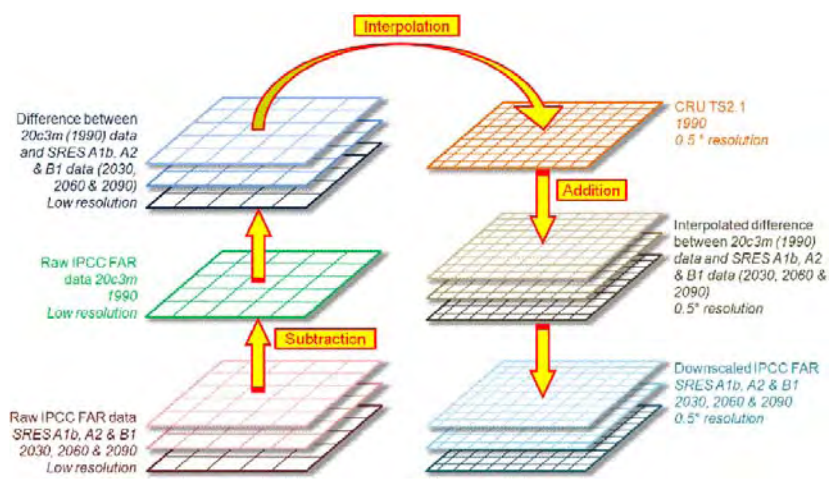
The climate model output variables that we considered for this analysis are total cloud fraction, precipitation, mean surface temperature, minimum surface temperature and maximum surface temperature. A summary of the models used for each climate variable is presented in Table 1.

This derived monthly mean data for each benchmark year was then used as an input to the next stage, Climate Model Downscaling, which develops the higher spatial resolution climate model data more suitable for the scale of the Albertine Rift landscapes.

Step 2: Climate Model Downscaling

The climate model data from the IPCC Fourth Assessment Report is developed for global scale applications, and due to computer processing limitations, among other factors, is of a relatively low spatial resolution. In order to evaluate climate change at the scale of the Albertine Rift, where surface spatial heterogeneities such as high topographic relief are inherent characteristics, much higher spatial resolution is required. One means to achieving this is to use a technique called statistical downscaling to interpolate lower resolution GCM results onto a higher spatial resolution surface.

Developing higher resolution climate data from the GCM output serves two important project needs. First, it enables evaluation of spatial variability in more detail across the Albertine Rift including at specific case study areas of particular interest to biodiversity conservation. Second, it provides higher resolution climate variable inputs for the ecosystem and vegetation and crop modeling components of the project.



Overview of the downscaling approach

Three main inputs are required for statistical downscaling. The first is the low resolution GCM predictions, the second is a set of low-resolution present day or historical data which provides baseline reference to the future predictions, and third is a set of higher resolution observed climatological parameters which can be used as a basis to develop statistical relationships on which to perform the downscaling.

A more detailed explanation is provided in provided on the website, along with a technical report, *Climate Model Data Downscaling, and Crop Model Simulation* (P. Thornton 2009, unpublished report available at:
http://programs.wcs.org/albertineclimate/Docustore/tabid/428/Default.aspx?Command=Core_Download&EntryId=3938

Step 3: Ecosystem Modeling

The Lund-Potsdam-Jenna (LPJ)[2] model is one of a number of Global Vegetation Models currently used to simulate changes in vegetation and associated bio-geochemical processes in response to climate change. The WCS Climate Assessment project utilized the LPJ model to develop an understanding of the potential impacts of climate change on the ecosystem function of the Albertine Rift, in addition to evaluating the potential impacts on major habitat (vegetation) types. We extend our thanks to Dr. Ruth Doherty of the University of Edinburgh, Scotland who generated the LPJ model output for the Climate Assessment and contributed information describing its products.

The version of the model used in this project was LPJ v1.2 - a full technical report on the set-up and execution of the LPJ model for this project, titled *LPJ_Technical Manual*[3] is available for download in the resources section of the project website. There are also journal articles by Sitch et al. (2003) and Gerten et al. (2004) which describe the LPJ model in detail.

Aside from the standard inputs to LPJ of Soil Texture and Atmospheric CO_2. concentrations, climate data input to the model consisted of the following:

1. CRU TS2.1 baseline climate data for 1990 (1980 - 2000)
2. Five downscaled (0.5 degree resolution) GCMs: *ncar-ccsm3* (4runs), *csiro-mk3.5* (1run), *miroc3.2(medres)* (2 runs), *miroc3.2(hires)* (1 run), *echam5* (1 run) - in total = 9 GCM simulations
3. 3 future SRES scenarios: B1, A1B & A2
4. 3 time slices: 2030 (2020 - 2040), 2060(2050 - 2070) & 2090 (2080 - 2100)

The LPJ model was run on each combination of the above, resulting in a total of 73 model runs (3 of the GCM simulations did not have data for the SRES A2 scenario). The results of the model are compiled into annual datasets (i.e. monthly variation is not identified).

Step 4: Crop Modeling

The rationale for developing models of future crop yield was to determine how the distribution of crop production under climate change will be different from the present day, and use this as a proxy indicator for the likely future distribution of people in landscapes containing protected areas, and the associated competition for natural resources. We extend our thanks to Dr. Philip Thornton

[2] http://www.pik-potsdam.de/research/cooperations/lpjweb
[3] http://programs.wcs.org/albertineclimate/Docustore/tabid/428/Default.aspx?Command=Core_Download&EntryId=3937

of International Livestock Research Institute in Nairobi, Kenya, who generated the crop distribution products for the WCS Climate Assessment project and contributed the following material describing its products.

The Decision Support System for Agro-technology Transfer (DSSAT)[4] is a global agricultural management model, which incorporates soil, climate, crop, phenotype and management data to determine agricultural productivity. In the model that was constructed for this project, only the climate component changed, therefore predictions assume that management, soils & crop phenotypes will remain in their present state.

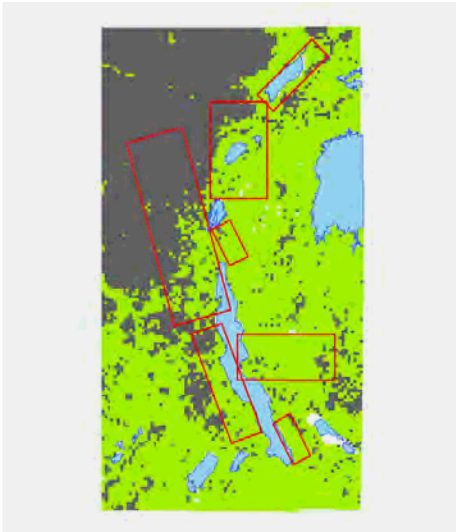
For this modeling exercise, DSSAT version 4 was used. A full technical report titled *Climate Model Data Downscaling, and Crop Model Simulation* detailing the procedures used during the agricultural production modeling stage as available at our project website.
An overview of the crop modeling work that was carried out is presented here. Three contrasting crops were chosen for future yield prediction. The first two, Phaseolus Beans and Maize, are widely cultivated in the Albertine Rift. The third is a forage species, *Brachiaria decumbens*, a grass that is highly palatable to livestock. Crop management practices for the maize and bean varieties were assumed at the current level of smallholder cultivation, with planting being dependent upon the onset of the rainy season and a nominal amount of inorganic nitrogen fertilizer (5kg per ha) being applied to the maize crop at planting. The model used for *Brachiaria* used the default variety in DSSAT, and simulated a grass-cutting system whereby the crop was cut 150 days after planting at the start of the main rainy season. As with the Maize crop, 5kg per ha of inorganic Nitrogen was applied as fertilizer.

In addition to present day (2000) climate normals from WorldCLIM (www.worldclim.org), climate inputs to the model consisted of the 5 Arc Minute downscaled climate normals for the following:

- 3 GCMs: bccr-bcm2.0, csiro-mk3.5, miroc3.2
- 2 SRES Scenarios: B1 & A2
- 3 time slices: 2030, 2060 & 2090

It is important to note that the results of the DSSAT modeling exercise indicate the *potential yields* for the modeled crops, as opposed to *actual yields*. That is to say that the given yield for a specific location indicates the yield that *could* be expected *if* that crop were grown there. Equally, the results do not indicate where the modeled crops are currently grown, only the areas where they could be grown. The second point is useful to remember when interpreting the results, as the first step in developing the models was to determine where pasture and cropland are potentially viable in the Albertine Rift. This assessment was made from the Agricultural Lands in the Year 2000 (http://www.geog.mcgill.ca/~nramankutty/Datasets/Datasets.html) dataset, developed by Ramankutty et al (2008). Only those areas defined in this dataset were included in the model - therefore the results indicate changes in agricultural productivity in areas that are currently suitable for pasture and cropping, but don't take into account potential changes in suitability of land for agriculture due to climate change. The impact of this on the analysis is demonstrated in Figure ___crop suitability___.

[4] http://www.icasa.net/dssat/



Model representation of Albertine Rift areas that are currently suitable (green) and unsuitable (grey) for pasture and cropping, according to Ramankutty et al (2008). The red boxes delineate the conservation landscape case study areas for reference.

Bearing this spatial limitation in mind, the results of the crop modeling exercise are nonetheless considered informative in determining the changes in natural resource availability for rural populations in the Albertine Rift, and the potential implications of these changes for both human populations and biodiversity.

Annex 2 – Raw data, analytical and information outputs

#	Dataset	Variables	Scenarios	Type	Years	Description
1	SRES Scenario Comparisons	Precipitation , Cloud Cover, Temperature	A2, A1B, B1	Monthly, % Change	1990, 2030, 2060 & 2090	Maps showing a comparison of predicted climate change under the A2, A1B & B1 SRES emissions scenarios
2	Climate Change	Precipitation , Cloud Cover, Temperature	A2	% Change	1990-2030, 1990 - 2060, 1990 - 2090	Maps indicating the extent of change in climatic variables between the present day and 2030, 2060 & 2090, predicted under the SRES A2 emissions scenario
3	Climate Model Predictions	Precipitation , Cloud Cover, Temperature	A2	Monthly	1990, 2030, 2060 & 2090	Maps showing the spatial distribution of climatic variables under the SRES A2 emission scenario from the present day to 2090
4	Crop Yield Predictions	Bean, Maize, Brachiaria	A2	Annual, % Change	1990, 2030, 2060 & 2090	Maps showing the spatial distribution of predicted crop yields under climate change modelled using the SRES A2 emissions scenarios
5	Future Ecosystem Function	Fire Carbon, Net Primary Production, Runoff	A2	Annual, % Change	1990, 2030, 2060 & 2090	Maps showing the spatial distribution and variability in different ecosystem function variables under climate change modelled using the SRES A2 emissions scenarios

6	Landscape Level Resilience to Climate Change	Precipitation, Temperature, Runoff, Net Primary Production, Heterotrophic Respiration & Total Carbon	A2	Extent of change outside present day landscape range	2030, 2060 & 2090	Topographic relief maps showing the spatial variation and degree that future climatic and ecosystem conditions will be outside the present day range of conditions.
7	Tutorials and Technical Manuals	-	-	-	-	Detailed information about technical procedures used to extract NetCDF data, run LPJ model and develop crop yield predictions
8	Raw IPCC FAR Climate Model Data	Cloud Cover (clt), Precipitation (pr), Mean Temperature (tas), Minimum Temperature (tasmin), Maximum Temperature (tasmax)	20c3m, A1B, A2, B1	Monthly	1990, 2030, 2060 & 2090	Raw low resolution IPCC FAR global climate model data for each individual model used to construct multi model means
9	Downscaled Climate Model Data	Cloud Cover (%), Rainfall (mm), Temperature (°C), Temp Diurnal Variation (°C)	A1B, A2, B1 & CRU Historical	Monthly	1990, 2030, 2060 & 2090	Downscaled medium resolution multi-model mean monthly climate normal data
10	Bioclimatic Profiles	1. Protected Areas 2. Biodiversity 3. Landcover 4. Mean Monthly Precipitation 5. Change in Mean Monthly Precipitation 6. Mean Monthly Temperature 7. Change in Mean Monthly Temperature 8. Mean Monthly Cloud Cover 9. Change in Mean Monthly Cloud Cover 10. Annual Plant Functional Type (PFT) . 11. Annual Net Primary Production 12. Annual Carbon Loss from Fire 13. Annual Heterotrophic Respiration 14. Annual Land-Atmosphere Carbon Flux 15. Annual Litter Carbon 16. Annual Soil Carbon 17. Annual Vegetation Carbon 18. Annual Total Carbon 19. Annual Actual Evapotranspiration 20. Annual Runoff 21. Annual Phaseolus Bean Yield 22. Annual Brachiaria decumbens Yield 23. Annual Maize Yield	A2, B1	Annual & Real Change	1990, 2030, 2060 & 2090	Bioclimatic profiles of the 7 selected case study sites. Includes mapped data for the Albertine Rift as a whole

11	Lund Potsdam Jenna Ecosystem Model Data	Actual Evapotranspiration, Total Runoff, Litter Carbon, Soil Carbon, Vegetation Carbon, Land-Atmosphere Carbon Flux, Net Primary Production, Heterotrophic Respiration, Carbon Loss from Fire, Plant Functional Type	A1B, A2, B1 & CRU Historical	Annual	1990, 2030, 2060 & 2090	Outputs from the Lund Potsdam Jenna ecosystem model – showing predicted ecosystem conditions at 2030, 2060 & 2090
12	DSSAT Crop Model Data	Bean Yield, Maize Yield, Brachiaria Decumbens Yield	A2, B1 & CRU Historical	Annual	1990, 2030, 2060 & 2090	Outputs from the DSSAT Crop yield model, showing predicted crop yields at 2030, 2060 & 2090
13	Python Scripts	-	-	-	-	Spatial analysis scripts written in the Python language to be run using ESRI ArcGIS Geo-processor
14	Compiled GIS Datasets	2010 Population Density - CIESIN AgroEcological Zones - IITA BioGeographical Zones - UNEP Easily Available Water - FAO Mean Growing period - FAO Soil Productivity Index - UNEP SPOT 2000 Landcover - FAO Water Availability - FAO	-	-	-	Various compiled datasets for the Albertine Rift in GIS format (ESRI Raster/Shapefile)
15	Presentations and Project Reports	-	-	-	-	Collection of presentations and reports generated during the project