Climatology and Potential Climate Change Impacts in the Nyungwe Forest National Park, Rwanda

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1. Introduction

The Nyungwe Forest National Park in southwestern Rwanda is one of the most biologically important afromontane forests of the Albertine Rift. Encompassing an area of 1,013 km^2, and altitudinal range between 1600 m and 2,950 m, it is the largest protected area in Rwanda, and when considered together with the conterminous Kibira National Park in Burundi, forms one of the largest protected tropical mountain forests in Africa, and is one of the six key landscapes identified for conservation in the Albertine Rift (Seimon and Plumptre, 2012). The Nyungwe-Kibira forest is recognized for its conservation importance and high levels of endemism: it represents a localized hotspot of biodiversity within the Albertine Rift, itself recognized as mainland Africa's foremost biodiversity hotspot (Plumptre et al., 2007). The national park protects a complex mosaic of vegetation types including montane forest, savanna grassland, bamboo forest and high altitude wetlands. The park is the subject of long-term research attention, with fairly comprehensive monitoring activities for both fauna and flora (Chao et al. 2012). While much of the forest currently exists in a close semblance of its original state, a century of profound land surface changes have totally transformed the neighboring environs, to the extent that it exists as a forest island remnant in a landscape completely transformed by human action from its past natural state (*Ibid.*) (Figure 1.1)

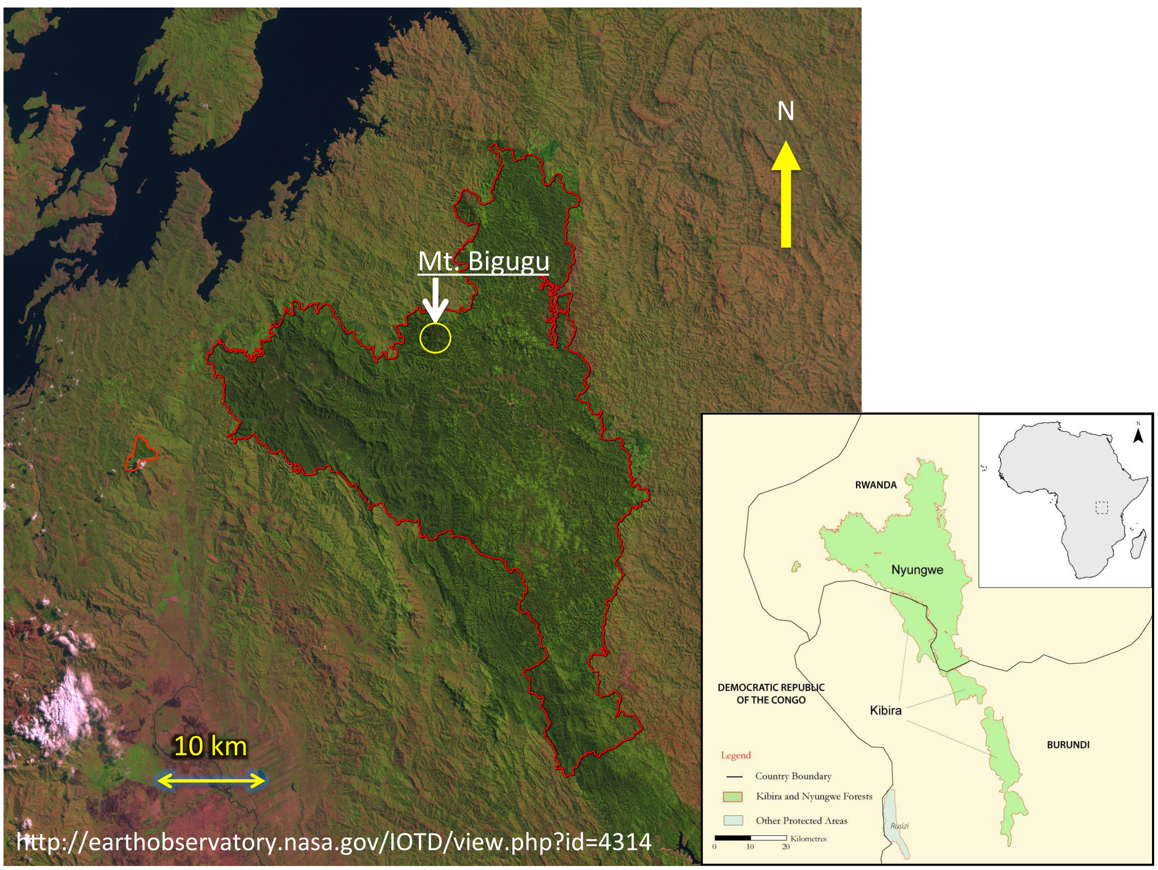

Fig 1.1: Nyungwe-Kibira appears as a forest island surrounded by heavily anthropogenically modified land when viewed from space. Source: NASA Earth Observatory (http://earthobservatory.nasa.gov/IOTD/view.php?id=4314)

The Nyungwe Forest National Park's landscape (hereafter Nyungwe) plays a vital role in intercepting precipitation and channeling run-off in the headwaters region of Africa's two largest hydrological networks, the Nile and Congo basins (Chao et al. 2012). As such, the ecosystem services provided by this protected landscape are crucial to the sustainability of local farming systems, primary industries (tea production, coffee washing stations, etc.) and the country's economy, through the provision of water and hydroelectricity as well as regulation of local and regional climate conditions. Nyungwe represents Rwanda's most important water catchment, ensuring dry season water supply for much of Rwanda, and the joint Nyungwe-Kibira forest catchment also supplies water to a hydroelectric power plant that produce 90% of electricity consumed in Burundi (*Ibid.*).

Conservation management of the Nyungwe Forest is conducted by the Rwanda Development Board (RDB) in close partnership with the Wildlife Conservation Society's Rwanda Country Program (WCS-Rwanda). Through their joint efforts, RDB and WCS-Rwanda have demonstrated considerable success in managing a variety of threats to the forest and its resident species, which include 13 primates, and hundreds of birds (Chao et al., 2012). With ecological tourism being actively promoted, the national park is increasingly viable economically and is seen as a critical node for expanding the country's potential to draw international visitors beyond that already registered by mountain gorilla viewing at Volcanoes National Park, which is limited in its potential for increase by firm restrictions on gorilla viewing permits.

The significance of Nyungwe for biodiversity conservation, and building recognition that sustaining the forest serves national socioeconomic interests have made climate change a subject of growing concern for the future. Climate change presents a host of potential impacts across the Nyungwe landscape, introducing new threats and exacerbating others already extant to the species and human populations that depend upon its biodiversity resources and the ecological services that the protected forest provides. The emergence of anthropogenic climate change as a stress factor is increasingly being considered in the conservation planning agendas for the Nyungwe Forest, as it is for Rwanda more generally. Comprehensive climate change assessments for Rwanda have been performed for the National Adaptation Program of Action series (NAPA) of the United Nations Framework Convention on Climate Change (NAPA-Rwanda, 2006), and through a series of reports by the Smith School of Enterprise and the Environment at Oxford University, UK (Smith School, 2011). Output from a variety of climate models evaluated for the IPCC Fourth Assessment Report generally project a warmer and wetter future for Rwanda, although as the Oxford University studies demonstrated, considerable spread exists in results from the individual models with two projecting slightly drier conditions (Figure 1.2).

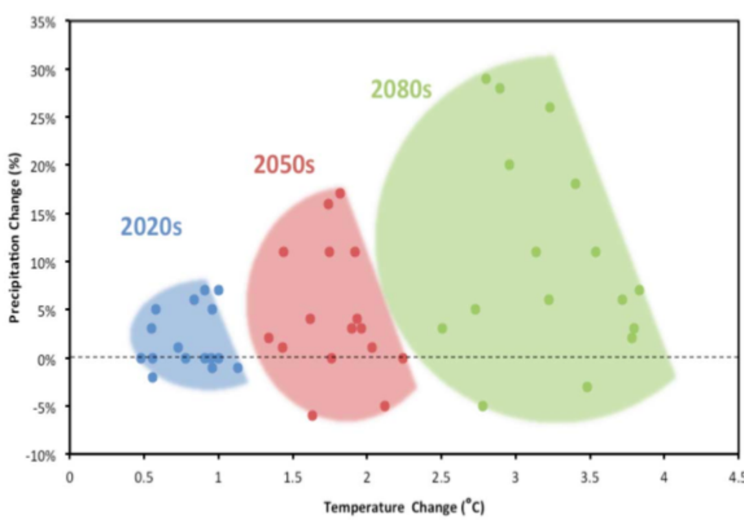

Figure 1.2. Different model projections of relative changes in temperature and precipitation from baseline conditions in Rwanda for three decadal periods of the 21st century as presented in the Oxford University vulnerability study. Reproduced from McSweeney.

Climate change assessments focused more locally on the Nyungwe Forest and its environs have been primarily concerned with relating aspects of the parks biodiversity and ecosystem services to projections of future conditions informed by numerical modeling. Studies performed to date include the following:

1. The WCS Albertine Rift Climate Assessment, a set of studies on climate change throughout the Rift region with Nyungwe as one of several focal regions (Seimon and Picton Phillipps, 2012; http://www.albertinerift.org/Challenges/ClimateChange/tabid/7525/Default.aspx).
2. United States Forest Service study on potential vulnerability of Nyungwe's hydrological ecosystem service provision under hypothetical climate change (http://rmportal.net/library/content/translinks/2011/wildlife-conservation-society/2011-Watershed-Modeling-and-Management-Workshop-Rwanda)
3. Global Environmental Facility (GEF) survey of climate change related threats to Rwanda's wetlands, one of which, the Kamiranzovu Swamp, is a major highland peat bog located within the Nyungwe Forest (Matthews et al., 2011)

In addition, output from the Community Earth System Model (CESM: Gent et al., 2011; Lawrence et al., 2012) which has been provided to WCS by the U.S. National Center for Atmospheric Research (NCAR), will be presented and assessed in this study.

The aim of this report is to summarize findings to date on Nyungwe's climatology and its ecological vulnerabilities to climate change as informed by climatological analysis of present day conditions and predictions for the remainder of the 21st century. This report therefore combines a relatively detailed overview of Nyungwe's current climatology with predictions of future bioclimatic conditions, which along with socioeconomic changes hold the potential to create environmental conditions that differ significantly from the present day. The analyses of current climatology and climate trends are used to identify a series of questions that could potentially be addressed through modeling studies. Projections from two sets of modeling outputs, those of the WCS Climate Assessment and CESM initiatives listed above, are then presented and then used jointly to address the questions and to summarize the current state of knowledge and identify critical knowledge needs for adaption of conservation planning to accommodate climate change.

This report is structured as follows. The data and models analyzed in the report are described in section 2. The present day climatology of the Nyungwe Forest is examined in section 3, placing emphasis on observations made directly within the national park over the past two decades, and key findings from the analysis are used to frame the questions. Sections 4 and 5 detail the modeling approaches and selected outputs from the WCS Albertine Rift Climate Assessment and CESM, respectively. In section 6 these results are evaluated and the questions are reconsidered in the light of the findings generated from the modeling studies. Finally, section 7 offers conclusions and recommendation for further activities to extend and refine studies on climate change to more comprehensively inform conservation interests of the environmental future of this critically important afromontane forest.

2. Data

Climatological data

Observations of climatic conditions meeting international standards of the World Meteorological Organization (WMO: www.wmo.ch) have been few in Rwanda, and this is especially the case around the Nyungwe Forest. Nevertheless, there has been systematic "gray data" collection at several sites in and close to the park, which although performed without calibrated instruments and adherence to international protocols, is highly informative for establishing climatological baselines and variability characteristics (Table 1).

TABLE 1: Annual rainfall amounts (mm) and frequencies (days with measurable rainfall) observed in Nyungwe Forest and vicinity. Of the stations listed, only Uwinka and Mt Bigugu are actually located within the park.

Station	Elevation (m)	Annual rainfall (mm)	Frequency (days per year)	Years of record	Source
Gisakura	1946	2,241	233	N.A.	Storz (1982)
Gisakura Tea Estate	N.A.	1,822	178	2000-2009	Seimon and Picton Phillips (2010)
Uwinka	2455	1,744	N.A.	1988-1993	Sun (1996)
Uwinka (PCFN site)	2450	1,588	152	1996-2012	Seimon and Picton Phillips (2010)
Kamatsira/ Rangiro	1670	1,787	177	N.A.	Storz (1982)
Kitabi	2200	1,763	188	N.A.	Storz (1982)
Ntendezi	1600	1,813	207	N.A.	Storz (1982)
Mt Bigugu	2960	N.A	N.A	Since Nov 2011	This study

For this study the records obtained from the Uwinka ranger outpost near the center of the park are utilized extensively. A new data stream beginning in November 2011 from a calibrated weather station installed by WCS at the summit of Mt Bigugu, the highest point in the park (2,960m above sea level) is also referenced. Records from an instrumented tower in operation for several years at Uwinka to serve a forest carbon measurement program (Nsabimana 2009) have not been examined for this study, but would be of value in the future to validate the Uwinka records presented in this report and to provide additional detail on climatology in the park.

Models

This report presents products and offers evaluations of two of the modeling programs identified in section 1 that offer output for the Nyungwe Forest region. These are the WCS Albertine Rift Climate Assessment and the CESM global model, for which grid cell data was extracted for this study by NCAR.

WCS generated the Climate Assessment output in 2008-09 for a study on the broader Albertine Rift region that encompasses the Nyungwe Forest landscape (Picton Phillips and Seimon, 2009). The CESM model output was developed by NCAR for global modeling application unrelated to the present study. Dr. Peter Lawrence of NCAR provided the CESM output for the Nyungwe region and guidance on its interpretation for the purpose of this study. The modeling approach utilized by each of these programs is described in the model overviews provided in sections 4 and 5.

3. Present day climatology of the Nyungwe Forest

Precipitation climatology

The climate of Nyungwe is quite typical of a tropical montane forest, and is characterized by very small thermal seasonality and a long wet season extending from September to May, with much drier conditions during the mid-year months. Observed rainfall averages between 1,500-2,500 mm per annum (refer to Table 1). Meteorological data has also been collected from within the forest by researchers at Uwinka and analysis of four years of this data (between 1988 to 1993) by Sun et al (1996) shows the average annual rainfall during this period to be 1,744mm with average maximum and minimum average temperatures to be 19.6°C and 10.9°C respectively. The sociopolitical crises that afflicted Rwanda during the mid-1990s disrupted all data collections. Basic climate data collection was resumed at the field station at Uwinka in 1996 and continues to the present (Figure 3.1).

Figure 3.1: Climatological observation sites inside Nyungwe National Park as of November 2012. **a** (**upper left**): The site operated by WCS at the Uwinka Overlook, which has nearly continuous daily records since 1996; **b** (**right**): the instrumented flux tower at Uwinka, currently operated by the National University of Rwanda; **c** (**lower left**): the automatic weather station installed by WCS in November 2011 atop Mt Bigugu (2,960 m), the highest summit of the Nyungwe Forest.

Analysis of the daily observations from 1996-2012 shows that Nyungwe is characterized by an 8.5 month pluvial season starting in early September that transitions rather abruptly to a dry season punctuated by intermittent rainfall starting in May. The latter half of March currently exhibits the climatological rainfall peak, and rates of 7 mm/day are sustained for much of the month (Figure 3.2a). Noteworthy features in the annual rainfall cycle include the abrupt onset and termination of the wet seasons, in early September and mid-May, respectively. The cessation of rainfall in May is especially pronounced, with remarkably precise regularity over the period of observation yielding a near step-function change in rainfall rate over just 3-5 day, and is possibly of considerable significance to phenological processes of forest biota.

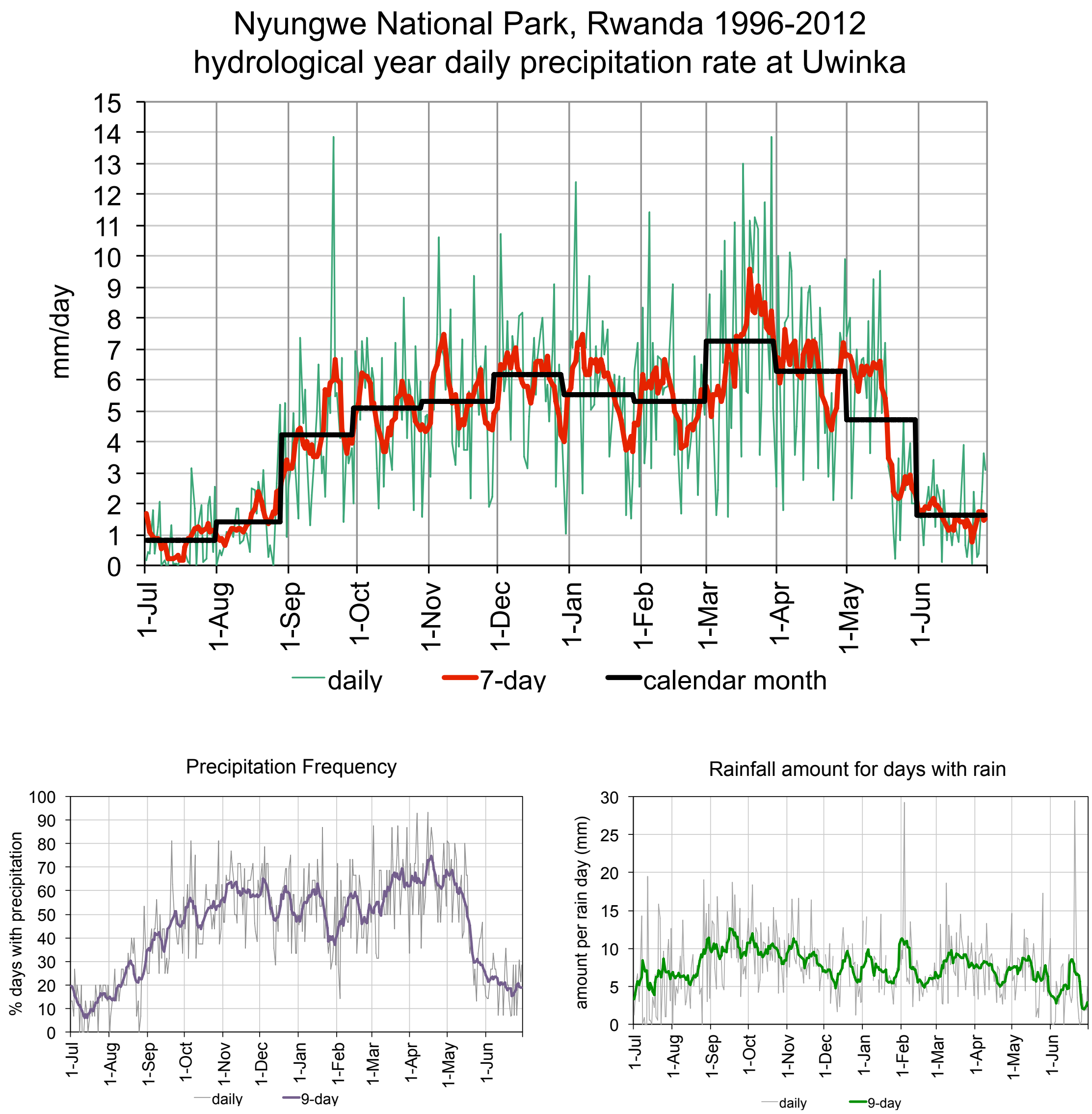

Fig. 3.2 .a (top): Hydrological year (July-June) averaged rainfall rate at Uwinka in Nyungwe National Park between the years 1996-2012, shown in mm/day for individual days, 7-day running means and calendar month averages. **b** (**lower left**): As above but for daily frequency and 9-day running mean in percent of measurable precipitation; and **c (lower right**) the daily average amount of precipitation and 9-day running mean in mm for days with measurable rainfall. The high-resolution data show highly pronounced climatological behavior at sub-monthly scales that is not apparent when aggregated into monthly means according to convention, as shown in **a**.

Another pattern of note are the twin reductions in precipitation rate in late January and again in late February. This reflects that Nyungwe is situated very close to the transition zone in rainfall seasonality separating unimodal rainfall regimes, characterized by a single long-duration wet season, from bimodal zones, where a short dry season in the Jan-Feb period separates the wet season into the Sept-Dec "Short rains" and Mar-May "Long Rains", as is experienced across much of equatorial East Africa (Seimon et al., In press). The temporary reductions in daily rainfall rate in Jan-Feb suggest that Nyungwe is sufficiently close to the transition zone to experience bimodality in its wet seasons in some but not all years. This also suggests an instability that might be influenced by atmospheric circulation adjustments related to anthropogenic climate change, and is discussed further in section 6. Further evidence for considering the wet season at Nyungwe as being comprised of two semi-distinct components can be derived from plots of rainfall frequency and intensity. The frequency of measurable precipitation ranges from a mean close to 10-20% from June through mid-August to two broad maxima averaging over 60% centered in November and April (Figure 3.2b). A fairly significant reduction to a short-term mean of 40% is observed in the latter part of January, again indicative of separation of the wet season into two components.

Another precipitation variable is rainfall intensity, which can be inferred indirectly by the amount of precipitation measured on each day that precipitation is observed. This reveals that the most intense precipitation events occur in the Sept-Nov Short Rains period, when the average wet day yields 10 mm of precipitation, while the pluvial peak in March occurs from a high frequency of lesser intensity events (Figure 3.2c). April exhibits the highest frequency of wet days, though these occur with relatively moderate rain rates per day. The wet season onset in early September is manifest mostly through an abrupt doubling of precipitation intensity, whereas the frequency of wet days exhibits a relatively monotonic increase during this period. Conversely, the wet season termination in mid-May is far more evident in an abrupt drop in wet day frequency than in event intensity. These characteristics give added definition to precipitation seasonality beyond those evident in the daily precipitation rate data alone.

Precipitation trends

For all of Rwanda, the Oxford University study identified no significant precipitation trends in the observational data between 1931-90 (McSweeney 2011), but this analysis does not represent current conditions. The data from Nyungwe-Uwinka was recorded after the period assessed by the Oxford study, and has markedly different results. The annual mean accumulation at Uwinka over the period 1996-2012 is 1,638 mm, yet a distinct trend is evident if the observations are divided in early and later periods, as shown in Figure 3.3. The mean annual precipitation from 1996-2004 was 1,519 mm; for 2005-12 the mean increased by 238 mm to 1,757 mm. The time periods considered are not long enough to fully ascertain whether the large increase reflects decade-scale variability that might be a short-term phenomenon or a true change trend, but the magnitude of change is quite significant, amounting to a 15.7% increase between the early and later periods. The trend of increase is fairly evenly distributed throughout the hydrological year (green line), with only minor deviations from the linear regression of the series (dashed line).

The installation of the automatic weather station atop Mt Bigugu in November 2011 allows comparison of measurements over a common period of record with the manual observations from Uwinka, which is about 4 km distance and 500 meters lower in elevation (Figure 3.4). These rain gauge observations show close agreement through the end of March, when several large magnitude precipitation events atop Mt Bigugu are not equaled in the Uwinka observations creating a disparity near the end of the period. The strong correspondence between the two sets of measurements confirms the occurrence of well-defined precipitation patterns and magnitude of rainfall during the period. The Nyungwe rain gauge data during the period of data overlap (9 Nov-30 April) was characterized by above normal precipitation in Nov-Dec, a short dry season in Jan-Feb, and resumption of significant precipitation during March and April.

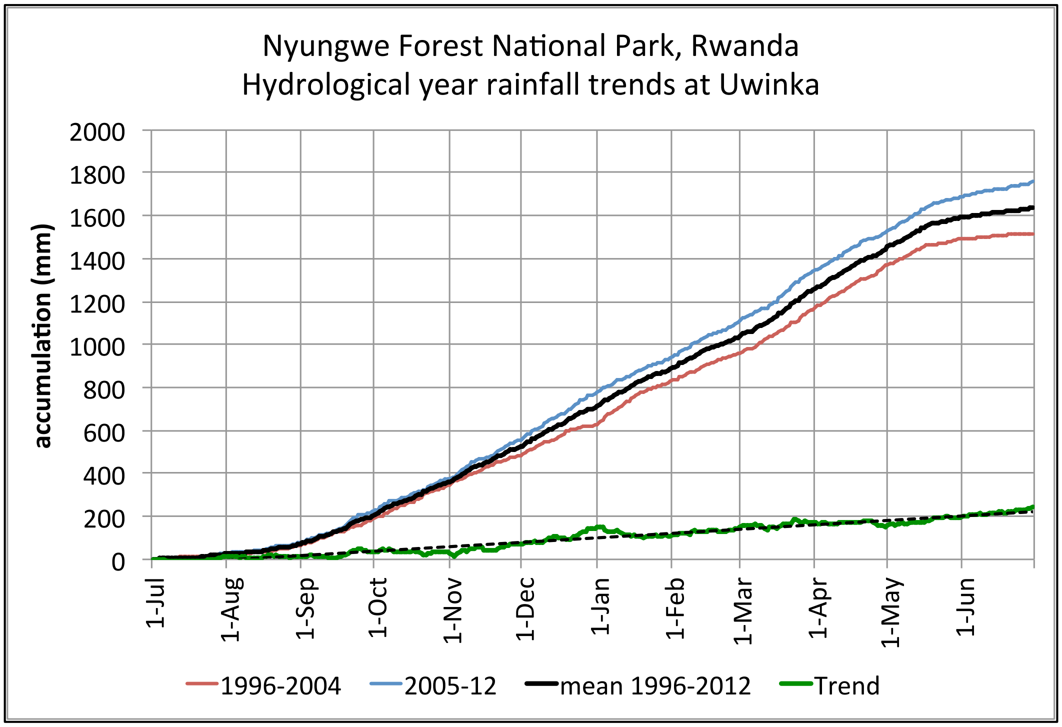

Figure 3.3. July-June hydrological year precipitation accumulation curves for Uwinka in Nyungwe Forest National Park for all years 1996-2012 (black line), and early and late periods thereof for 1996-2004 (red) and 2005-2012 (blue). The green line shows the difference of 1996-2004 minus 2005-2012 through the course of the hydrological year, with the overall trend indicated by the regression line (dashed).

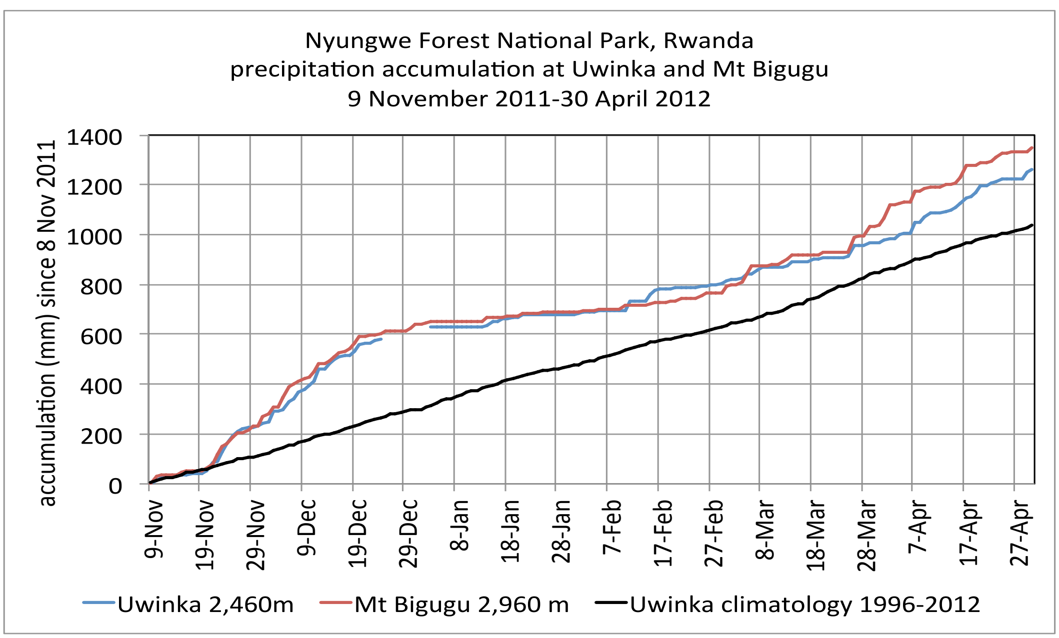

Figure 3.4: The Nov-April subsection of accumulation for the 2012 hydrological year comparing simultaneous observations from Uwinka and Mt Bigugu with contemporaneous baseline climatology means derived from the Uwinka daily precipitation data from 1996-2012.

Remote sensing of precipitation

Satellite-based rainfall measurements are increasingly utilized to provide proxy measurements of rainfall in tropical Africa in the absence of surface-based observational networks (Seimon et al., in press). Such measurements are of considerable utility at broad spatial scales, but are of uncertain reliability in more focused localities. An example comparing actual gauge measurements from the Uwinka and Mt Bigugu weather stations with satellite estimated rainfall for a much larger geographic domain centered close to Mt Bigugu region during the 2011-12 hydrological year is presented in Figure 3.5. The satellite data utilized for this comparison is the NASA Tropical Rainfall Measuring Mission (TRMM) space-borne radar system (http://trmm.gsfc.nasa.gov/).

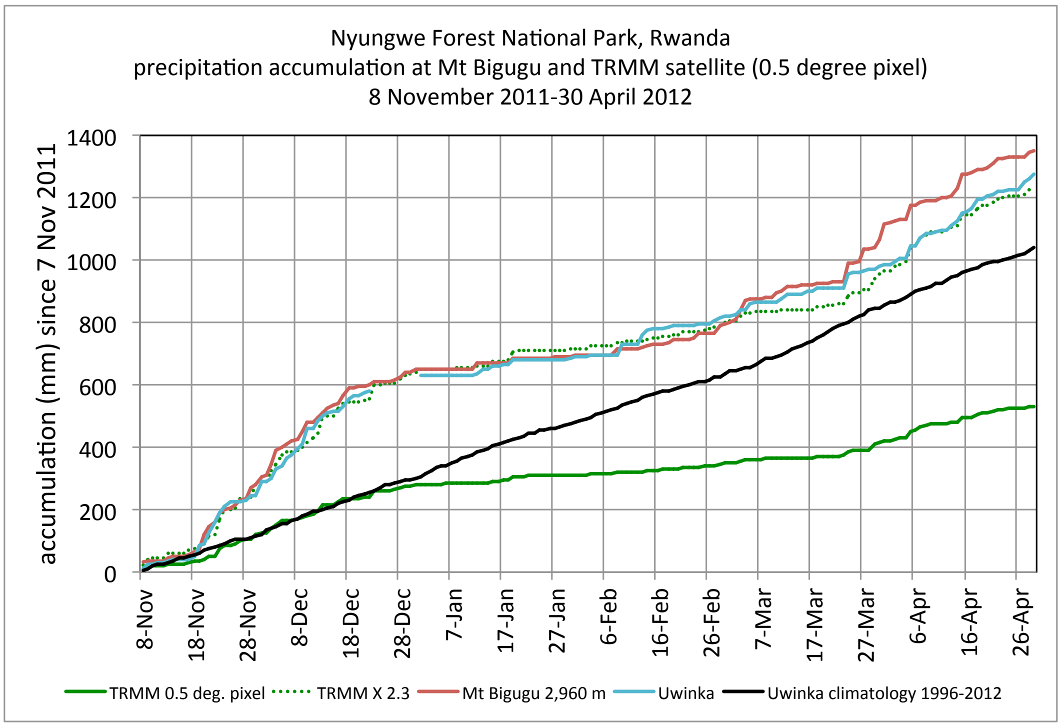

Figure 3.5. Tropical Rainfall Measuring Mission (TRMM) satellite-borne radar estimate of accumulating rainfall across a 0.5 x 0.5 degree (56 x 56 km) lat-lon grid cell centered close to Mt Bigugu in Nyungwe Forest National Park, Rwanda compared to the climate station data shown in Figure 3.4. TRMM data (solid green line) becomes a much closer fit to the other data when multiplied by 2.3 (230%). TRMM data was downloaded from NASA (NASA 2012).

The TRMM measurements significantly underestimate the gauge-based observations, yet if plotted as 2,3 times the reported amounts yield a very close fit. This suggests that either the algorithm applied to the satellite observations might require adjustment, or that the gauge observations being performed in the most elevated part of the TRMM pixel domain might have especially high rainfall relative to the greater region. Most likely, the discrepancy is due to a combination of both factors. Therefore, while this result identifies that satellite-based precipitation measurements are potentially valuable for establishing rainfall rates and spatial characteristics in and around Nyungwe, reliable gauge measurements are still needed as a means of providing ground-truth checking and correction to establish the appropriate scaling.

Temperature

Daily maximum and minimum temperature data has been recorded at Uwinka since 1996. A high-temporal resolution climatogram derived from these data show that the dry season features reduced maxima and minima, with annual minima for both recorded in July while the sun is at zenith in the northern hemisphere. The rapid onset and cessation of the rainy season is not reflected in the thermal data (Figure 3.6).

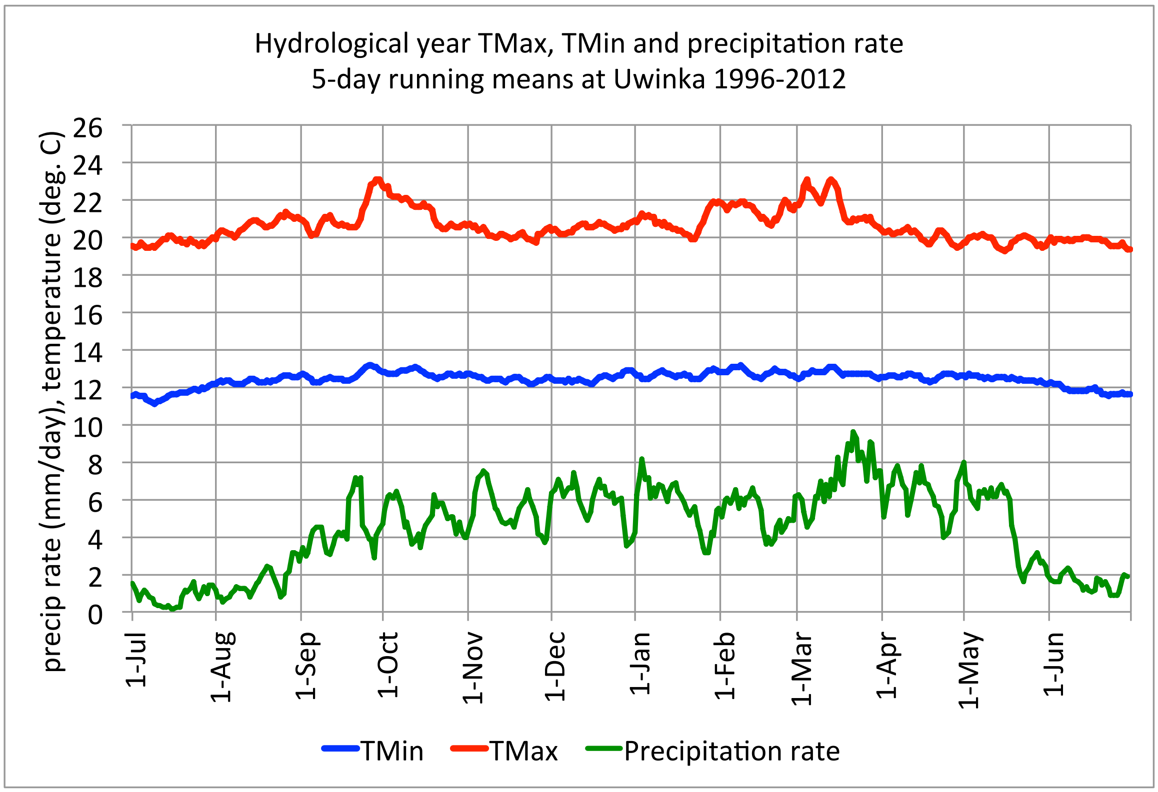

Figure 3.6: Climatogram displaying 5-day running means of maximum (TMax) and minimum (TMin) temperature as well as precipitation rate (mm/day) for Uwinka in Nyungwe National Park, Rwanda based on daily data collected from 1996-2012.

The most significant patterns are two pronounced multi-week positive departures in daytime temperature maxima that peak in late September and early March, respectively. These are striking for their temporal symmetry, being approximately equidistant in time from the December solstice, their considerable magnitude and for their occurrence during the wet season when heavy cloud cover tends to be persistent. These factors cast some doubt on the reliability of these observations. Analysis of the maximum temperature data shows that the anomalous thermal peaks correspond with high variance in the daily records, which is only registered consistently around these times of year (Figure 3.7). This appears to be the product of observational biases associated with the placement and use of non-standard housing for the thermometer for much if not all of the observational period (Seimon and Phillips, 2010). This possible problem was communicated out to the observers in 2009, and the thermometers were relocated from the exterior wall of a building to the instrument shelter shown in Figure 3.1a. The shelter is colored dark green, however, rather than the white required to minimize solar absorption during meteorological observations, hence it is still subject to inappropriate levels of heating during daytime hours. For this analysis, all daytime measurements from the Uwinka site are therefore considered to be unreliable, with a positive bias that is likely amplified on days with direct sunshine.

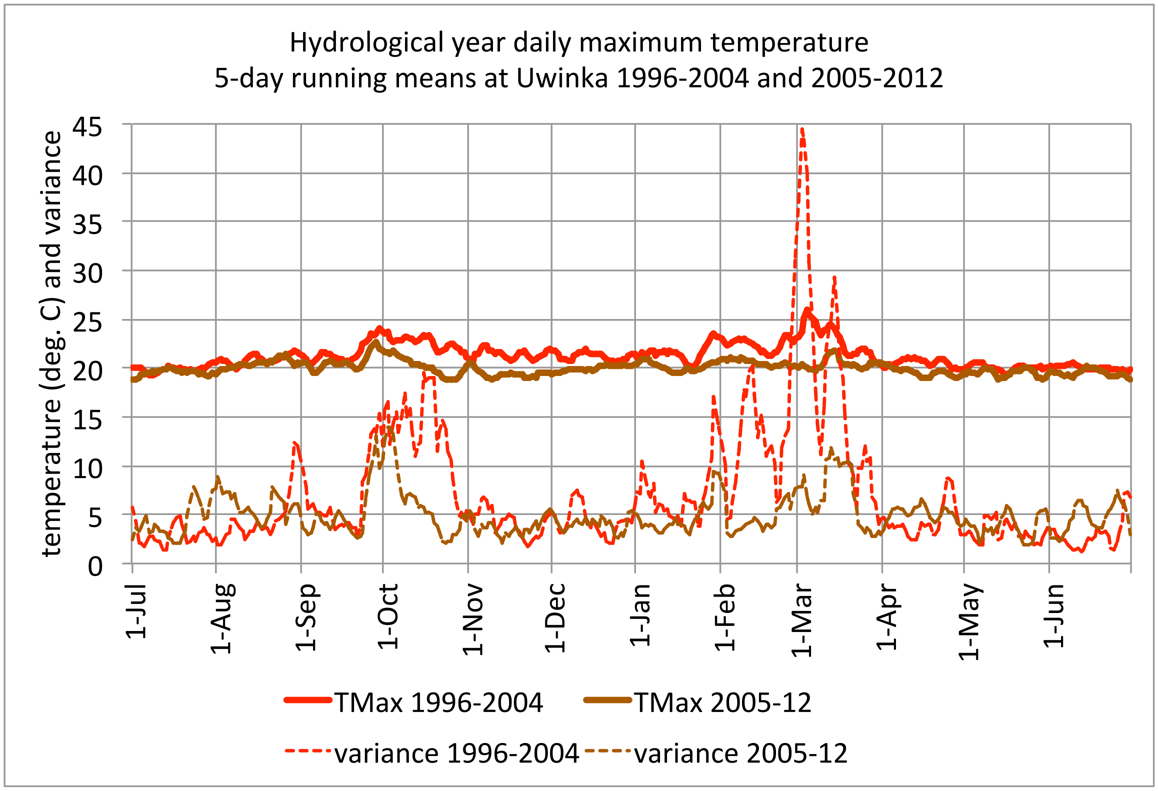

Figure 3.7. Five-day running means of hydrological year daytime maximum temperature data (°C) for Uwinka in Nyungwe Forest National Park for 1996-2012 separated into early (1996-2004, red line) and later (2005-2012, brown line) periods, with the variance from each periods shown in dashed lines in the corresponding colors.

A comparable analysis for daily minimum temperature yields strikingly different results that support its relatively reliability for representing overnight thermal conditions in the Nyungwe Forest through the course of the year. The split time series exhibit very similar temperature patterns through the course of the hydrological year, with variances an order of magnitude lower than those exhibited for daily maximum temperature (Figure 3.8). The stability of the minima can be inferred to be results of nocturnality, where lowest temperatures are typically registered in the predawn hours and thus not subject to interference related to solar irradiance. Another aspect of thermal stability is the extremely low variation of minima throughout the year, with average nocturnal temperatures varying between 11-13°C.

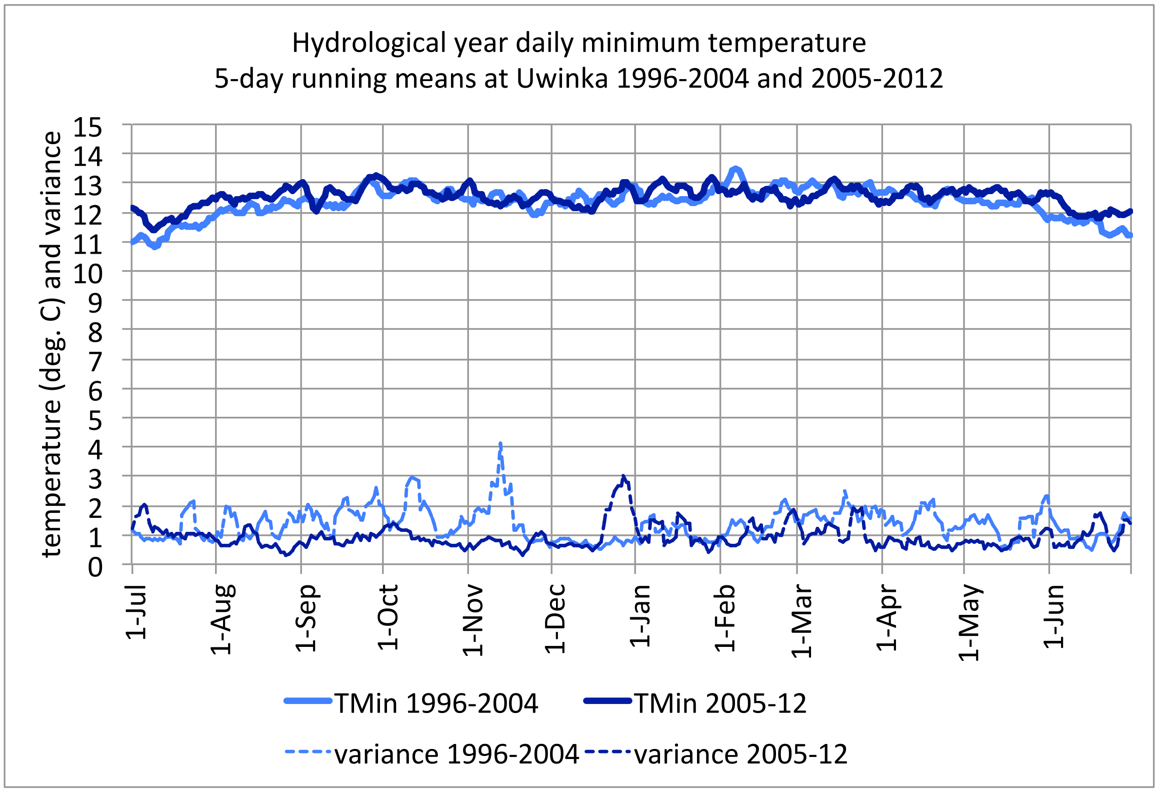

Figure 3.8. Five-day running means of hydrological year daily minimum temperature data (°C) for Uwinka in Nyungwe Forest National Park for 1996-2012, separated into early (1996-2004, light blue) and later (2005-2012, dark blue) periods, with the variance from each periods shown in dashed lines in the corresponding colors. Note the shift in scale from Figure 3.6.

Temperature trends

For all of Rwanda, the Oxford University study identified a trend of rapid temperature increase averaging 0.35°C per decade, with diurnal maxima and minima exhibiting similar increases over a 40-year period leading to the present (McSweeney 2011). A similar trend was recorded between 1953-2006 from the Lwiro Research Station near Bukavu in eastern Democratic Republic of Congo, approximately 100 km from Uwinka (Seimon and Picton Phillipps, 2012). It is therefore quite likely that the Nyungwe Forest is experiencing significant warming of the local climate, though the magnitude remains to be ascertained. Due to the clear evidence of observational biases, the split time series for diurnal maxima presented in Figure 3.7 cannot be utilized to establish if a trend exists between the earlier and later periods. It may be a possible to more accurately ascertain diurnal maximum temperature behavior by analyzing the Uwinka data with the new data stream from the Mt Bigugu weather station and also the carbon sequestration study site, also at Uwinka, once more years have been sampled.

For daily minima, the observation bias issues are clearly reduced, so the data can be examined for inference on trend behavior. The difference between the annual means from the early to the later period, centered on the years 2001 and 2008, respectively, shows an increase from 12.35°C to 12.52°C: this translates to a rate of +0.24°C per decade. The data in Figure 3.8 shows that most of the increase has been registered in the May-September dry season.

Fog

Fog is a common climatic feature in the moist forest environments of Nyungwe, and likely of considerable importance to the ecology of many highlands plant and animal species. Casual observation suggests that fog adheres mostly to forested terrain and the peripheral forest buffer zone covered by tea plantations, and is much less frequent across land cleared for cultivation. There is as yet no systematic monitoring of fog so little can be stated about its frequency, geographic preferences, trends or relationship to flora and fauna.

A note on meteorological conditions associated with fire occurrence

Fire is a recurrent phenomenon in the Nyungwe Forest, and is fostered by the meteorological conditions accompanying the mid-year dry months. Most fires in Nyungwe appear to be anthropogenic in origin, ignited by people collecting various forest products including honey, wood and bush meat, and the absence of fire-adapted flora suggests that fire has not been prevalent historically nor is a major selective force within the forest ecosystem (Chao et al., 2012). Activity observed in recent years shows that fires that originate during the mid-year dry season can become very intense crown fires lasting many days; a substantial amount of the forest (nearly 13,000 ha, or 12% of the national park) was lost to wildfires between July and October in 1997, with complete loss of above-ground vegetation (*Ibid.*). This particular year featured an exceptionally arid and prolonged dry season that desiccated vegetation, causing it to become highly vulnerable to wildfire. The Uwinka rainfall observations show that the Short Rains onset in the 1997-98 hydrological year occurred six weeks later than normal, in mid-October of 1997, allowing fires to spread unimpeded while capitalizing on exceptionally desiccated vegetation and forest litter (Figure 3.9).

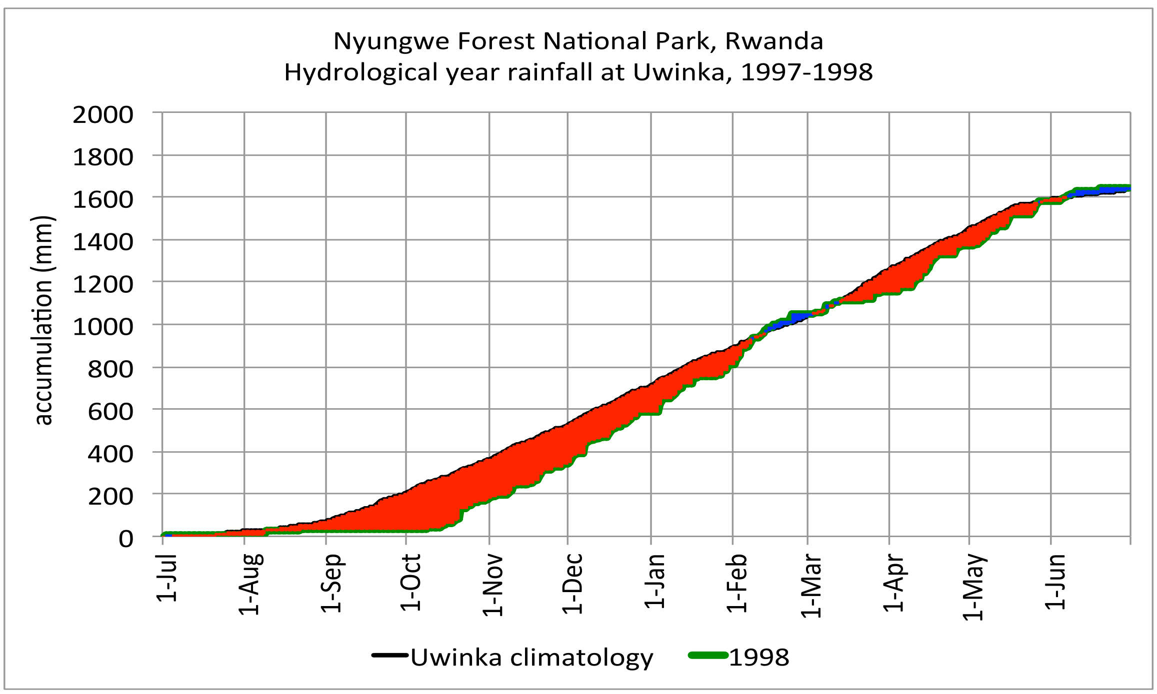

Figure 3.9: Hydrological year precipitation accumulation at Uwinka for the 1997-98 hydrological year, highlighting anomalies relative to the 1996-2012 climatological means. Red shading indicates periods of precipitation deficit relative to the long-term mean, and surpluses are shown in blue. The July-October period in 1997 featured widespread fires in Nyungwe during the period of extended aridity.

Findings on local climatology related in ecological contexts

- Precipitation seasonality is the dominant characteristic of Nyungwe climate, and appears highly prone to perturbation. There are several well-demarcated signals in the current annual cycle that can readily be monitored for temporal and magnitude changes.
- Nyungwe resides at a transition zone between unimodal and bimodal rainfall seasonality. The Jan-Feb dry period that occurs in some years indicates this climatic instability, and that Nyungwe's current climate resides close to a tipping point threshold of separation into two distinct pluvial seasons.
- The annual pluvial peak currently occurs in the latter half of March, and presumably corresponds with a subsequent peak in hydrological runoff (although stream flow data was not analyzed for this study).
- A trend of increasing precipitation is strongly evident, though cannot be conclusively confirmed given the limited length of the period of record.
- Nocturnal temperature minima show extremely small variations throughout the year on both a day-to-day and seasonal basis. This suggests that species with high thermal sensitivities (e.g. amphibians and chameleons) may show strong distributional preferences for well-defined elevational niches.
- A secular trend of rapidly increasing temperatures is currently in progress, and is consistent with expectations of anthropogenic greenhouse gas-induced warming.
- The multi-decadal trend of increasing temperature observed regionally is almost certainly driving a corresponding altitudinal increase of isotherms. This represents a direct climate change forcing upon thermally sensitive biota, which may respond through vertical range extensions and contractions that should be readily detectable by systematic monitoring applied along elevational gradients.
- Fire occurrence is related to seasonal desiccation of vegetation during the mid-year dry months, though ignition occurs from human activities tied to illicit extraction of forest resources making trend behavior tied to climatic conditions difficult to ascertain.
- The conjoined Nyungwe-Kibira national parks are effectively a remnant forest island encompassed entirely by heavily modified anthropogenic landscapes where croplands are the primary land surface type. The microclimatology within the forest should therefore be expected to differ markedly from conditions experiences in adjacent croplands.

Applying these findings to biodiversity conservation brings several key issues to light. For the Nyungwe Forest landscape some critical questions for biodiversity conservation planning and management relevant to climate change in coming decades are the following:

Q1. Will the Nyungwe forest remain extant for the foreseeable future?

Q2. Are biome transitions to be expected?

Q3. How will climate change impact human land use bordering the park, and what are potential consequences of such changes?

Q4. Is the current intensifying fire regime indicative of a trend or variability?

Q5. Is Nyungwe's long wet-season season splitting into two distinct parts, matching the bimodal rainfall pattern currently experienced nearby to the north?

Q6. How will the magnitude and relative proportion of early and late season rains change?

Q7. How will hydrological release from the Nyungwe Forest during the dry season, critical for Rwanda's agriculture and hydropower, develop over time in response to climate change?

Q8. How will the carbon sequestration potential of the landscape change as climatic conditions and atmospheric CO_2 levels change?

Q9. How will climate change influence natural hazard occurrences in the landscape?

Informed inference for addressing these questions can be developed through examination of the results of numerical modeling studies that generate future projections of climatic and environmental states for the remainder of the 21st century. In sections 4 and 5 this is demonstrated through two different modeling approaches, with the questions readdressed in section 6.

4. WCS Albertine Rift Climate Assessment output for Nyungwe

The Climate Assessment project evaluated climate change and its potential effects on regional ecology across the Albertine Rift and within sub-regions of highest significance to biodiversity conservation. One of these focal regions is the Nyungwe-Kibira landscape of Rwanda and Burundi, for which global climate model and dynamic vegetation model outputs were generated to provide guidance on the potential changes to climate and environments across the 21st century under greenhouse-gas driven global climate change. The climate model inputs were derived from the means of an ensemble of 11 models from Phase 3 of the Community model Intercomparison Program (CMIP3; Meehl et al., 2007), which are among those utilized for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, released in 2007.

Modeling approach

There are four distinct stages to the data analysis: (1) data acquisition and pre-processing; (2) climate model downscaling; (3) ecosystem and crop modeling; and (4) spatial analysis. Baseline conditions for comparison to model predictions were developed from the University of East Anglia Climate Research Unit CRU TS2.1 interpolated baseline climate gridded data (Mitchell et al., 2004) averaged over the period 1980- 1999 to determine gridpoint values of monthly mean cloud cover, precipitation and temperature over the Albertine Rift project domain. The data from low-resolution general circulation model (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 and 2090. They were also used as an input to the 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 Picton Phillipps and Seimon (2009). The multi-step sequence is outlined in Figure 5.1.

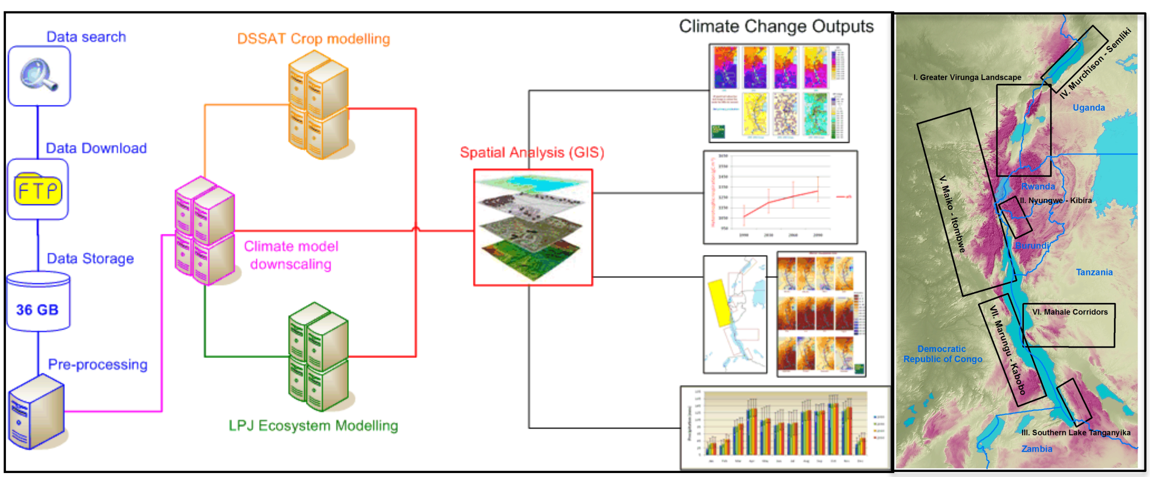

Figure 4.1: a (left) Schematic diagram demonstrating the procedure used to generate ecologically meaningful products specific to the Albertine Rift study domain from raw, low resolution GCM output. **b (right)** Map of the Albertine Rift modeling domain showing sub-regional landscapes assessed for the WCS study. The Nyungwe-Kibira landscape is encompassed by the small rectangle at the center of the figure.

The model output was generated under the A2 greenhouse gas emissions scenario (IPCC 2000). Under this projection of global economic development and demographic trends, human population is expected to increase at a high rate, with energy consumption and changes in land use correspondingly high. The Climate Assessment also projected all variables under the more moderate A1b and B1 emissions scenario. The focus here is on the more severe (although not extreme) A2 scenario since current global emission levels are already considerably above the levels prescribed in this scenario (Le Quéré et al., 2009)

The suite of products generated fall under four general categories: climate variables, carbon pools, carbon fluxes, and vegetation and agriculture as follows:

TABLE 2: WCS Albertine Rift Climate Assessment output variables	
Products available for the Nyungwe-Kibira sub-region of the Albertine Rift	
	Climate variables (monthly)
Temperature	Monthly mean temperature (°C)
Precipitation	Monthly mean precipitation amount (mm)
Cloud cover	Monthly mean cloud cover (percent of sky coverage)
Total Runoff	Sum of direct runoff and base flow arriving at a drainage channel for discharge via streamflow (mm)
Actual Evapotranspiration	Quantity of water actually removed from a surface due to the processes of evaporation and transpiration (mm)
	Carbon pools (monthly), in gC m-2
Vegetation Carbon	Amount of carbon stored in vegetation
Soil Carbon	Amount of carbon stored in the soil
Litter Carbon	Amount of carbon stored in dead organic matter
Annual Total Carbon	the sum of Vegetation, Soil & Litter carbon
	Carbon fluxes (monthly), in kgC m-2
Net Primary Production	Production of organic matter from atmospheric (or aquatic) carbon dioxide by plants in an ecosystem minus losses of carbon resulting from plant respiration
Land-Atmosphere flux	- Change in carbon storage between terrestrial ecosystems and the atmosphere
Carbon Loss from Fire	Amount of carbon emitted to the atmosphere each year through vegetation burning
Heterotrophic respiration	Amount of carbon released through the decomposition of dead organic matter
	Vegetation and agriculture
Maize	Annual Maize Yield (kg ha-2)
Bean	Annual Phaseolus Bean Yield (kg ha-2)
Pasture	Annual Brachiaria decumbens Yield (kg ha-2)
Plant Functional Type	Fractional Cover of Plant Functional Type (%)

Model outputs

Model outputs in terms of areal statistics and plots revealing trend behavior are presented here for several of the output parameters. Summary statistics of the several key variables yielded generated for the Nyungwe-Kibira landscape are presented in Table 3. Because the analyses were prepared for a much broader geographic domain with different hydrological year periods, the characterizations of monthly climate presented in this section are plotted in calendar years, rather than the July-June hydrological years presented in section 3.

TABLE 3 – A selection of climate, ecosystem and crop yield variables for the baseline year 1990 and predicted for 2030, 2060 and 2090 under the A2 emissions scenario for the Nyungwe-Kibira sub-region of the Albertine Rift. For each variable the Min and Max values indicate grid cell extrema within the sub-region; the Mean is the arithmetic average of all grid cells in the sub-region.

		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	

Temperature

Across the Nyungwe-Kibira landscape, the multi-model output projects strong and sustained temperature increases under the A2 emissions scenario, with a steepening rate of increase in the latter part of the century. Temperature increases are projected to occur relatively uniformly throughout the year, although the mid-year months exhibit slightly stronger increases by century's end (Figure 4.1). A net increase of 3.6 °C is registered over the 100-year period 1990-2090.

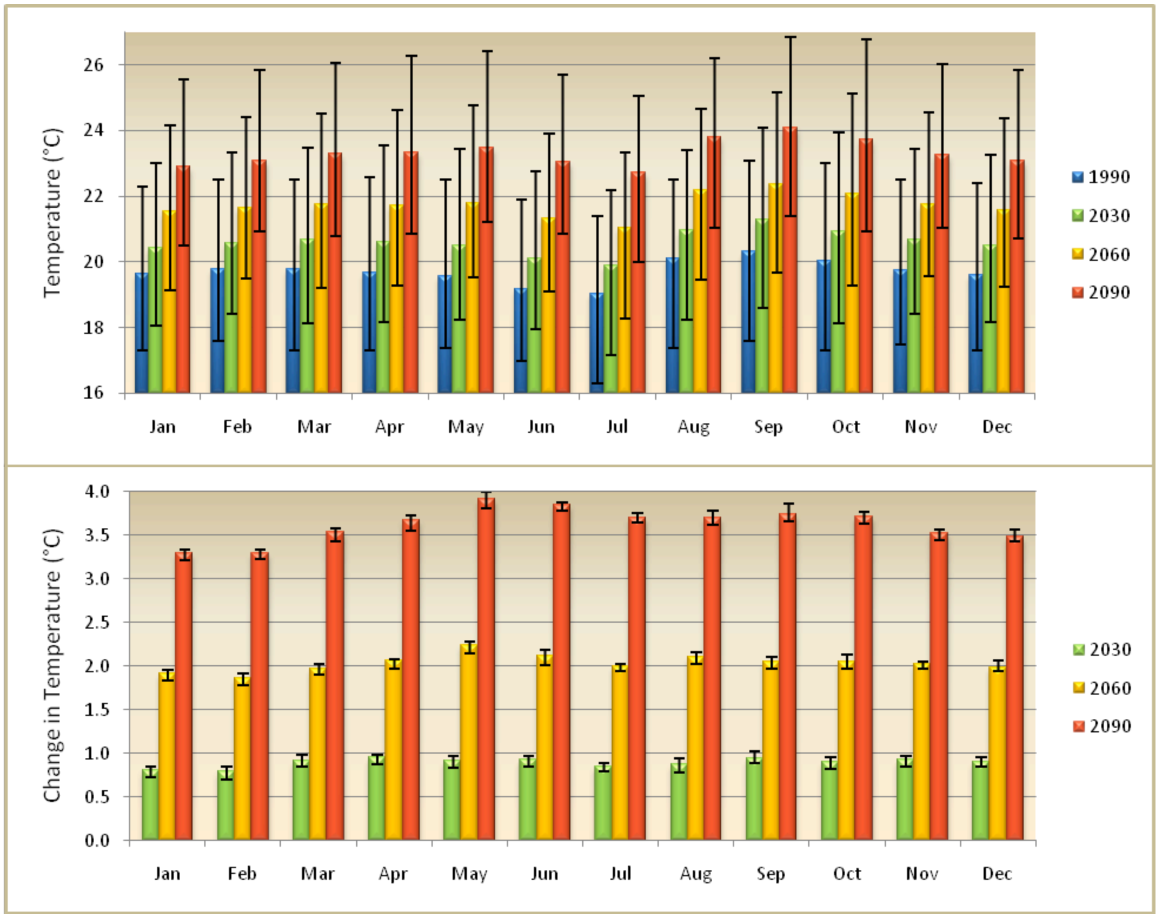

Figure 4.2: **a (top)** Mean monthly temperatures and **b (bottom)** temperature changes relative to the 1990 baseline data (°C) for the years 2030, 2060 and 2090 in the Nyungwe-Kibira region under the IPCC A2 greenhouse gas emissions scenario. The thin vertical lines show the range of grid cell values within the region, and are related to maximum and minimum elevations so display little variability in the output.

Precipitation

In contrast to the temperature projections, the monthly precipitation projections display marked seasonal differences as well as steepening rates of rainfall increase (Figure 4.3). By 2090, precipitation increases 13.5% over the 1990 baseline values, with the largest increase projected in the November-December. This yields a significant redistribution in the annual fraction of rainfall during the two wet seasons that characterize rainfall over much of the Albertine Rift. From mid-century onward, a large increase in November-December rainfall is projected while little net change is evident in the March April period. Of note is that for the 20-year period centered on 2030, slight decreases in monthly rainfall are depicted for mid-year, corresponding with the longer dry season, before this reverses to rainfall surpluses. Given the observed current relationship between fire occurrence and dry season aridity, such a pattern might be indicative of increasing threat of drought and forest fires, since rising temperatures would concomitantly promote stronger seasonal desiccation of the forest.

In the model depictions, the cloud cover remains relatively invariant over time (not shown). Taken together, these predictions outline the development of a markedly different regional climatic regime from by mid-century onwards, characterized by conditions of warmth and wetness that would register as extreme in the present day.

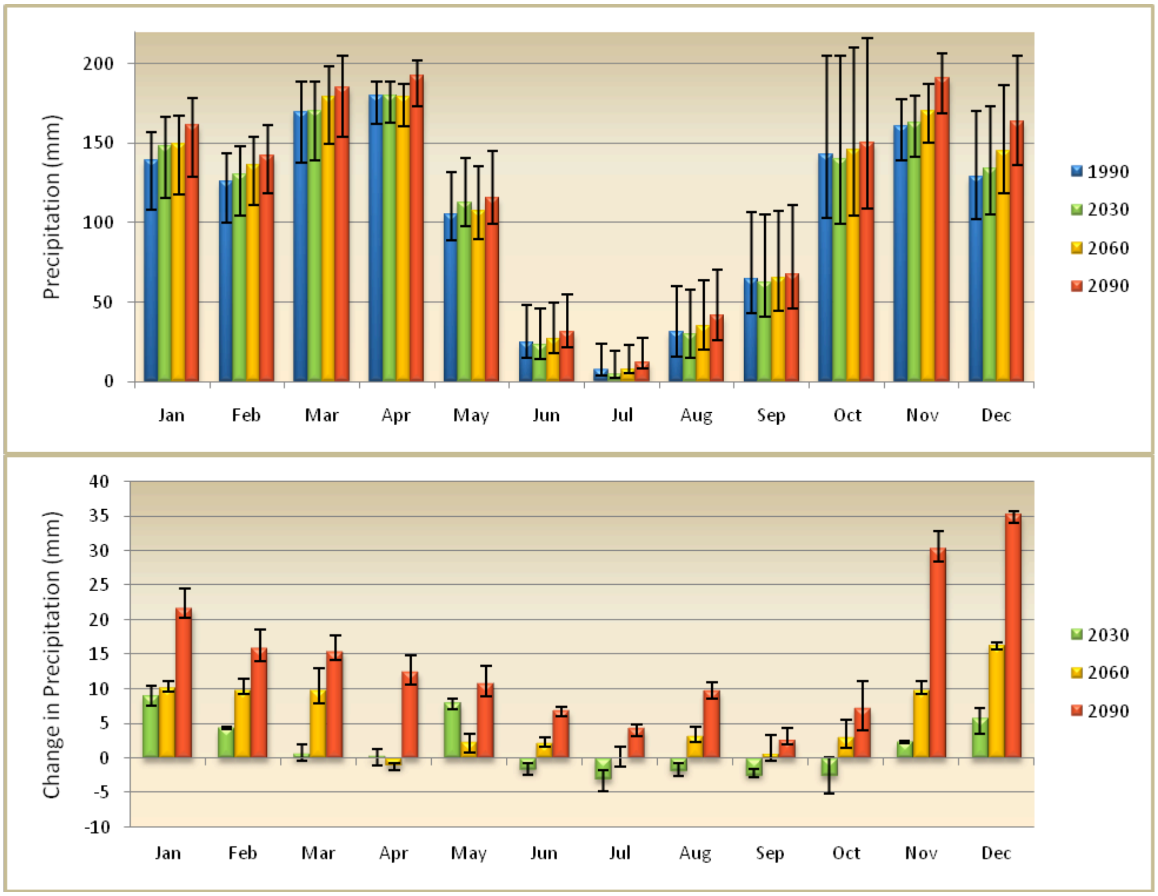

Figure 4.3: **a (top)** Mean monthly precipitation amount and **b (bottom)** changes relative to the 1990 baseline data in mm for the years 2030, 2060 and 2090 in the Nyungwe-Kibira region under the IPCC A2 greenhouse gas emissions scenario. The thin vertical lines show the range of grid cell values within the region.

Runoff

In the LPJ dynamic vegetation model output, the precipitation increases are predicted to yield a disproportional response in hydrological runoff (Figure 4.4a). The 13.5% rainfall increase between 1990-2090 yields a startling 70% increase in runoff, a result that seems implausible though has physical basis in the LPJ model's dynamic approach to vegetation response to changing atmospheric conditions. This can be interpreted as relating to model sensitivity to hydrological uptake by plants, whereby under hotter, wetter conditions within an atmosphere enriched in CO_2 increased stomatal closure in leafy vegetation arrests plant transpiration, leaving a greater fraction of precipitation available as runoff (Doherty et al., 2009). The LPJ output shows a corresponding decrease in evapotranspiration (Figure 4.4b). How well such a dynamical response to a warmer, wetter and CO_2-enriched climate matches the actual sensitivity of the Nyungwe Forest's biotic and hydrological systems is unknown.

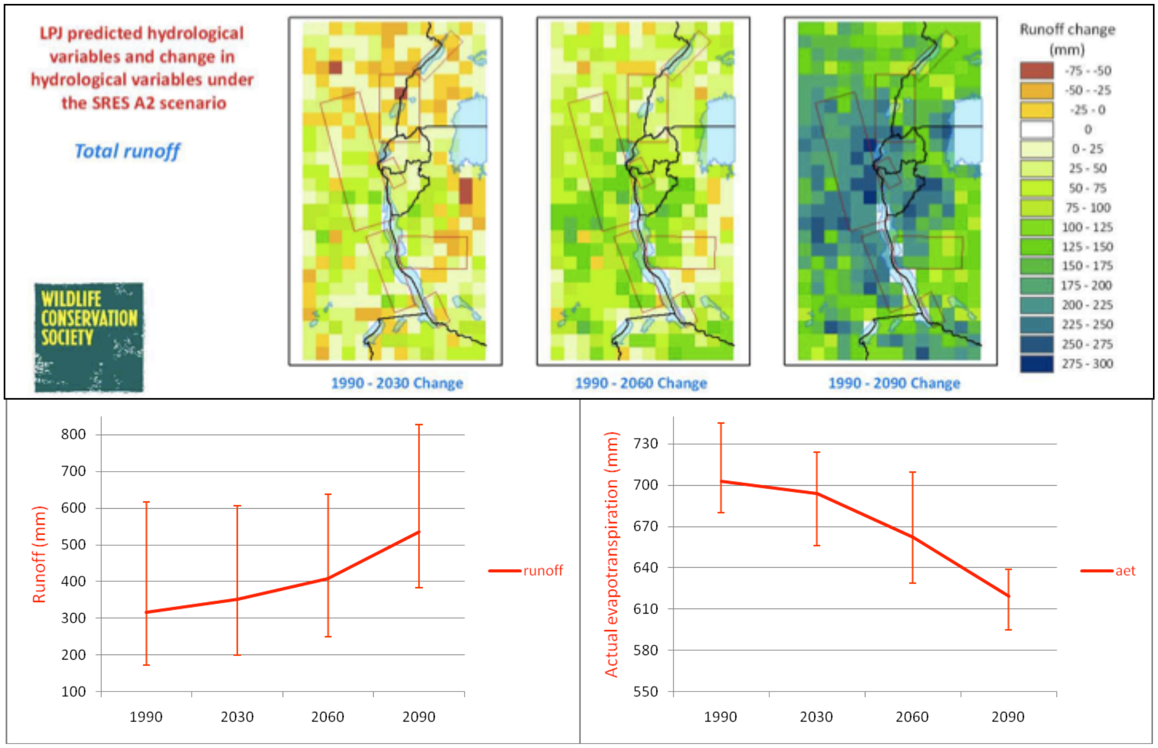

Figure 4.4: a (top) WCS Albertine Rift Climate Assessment spatial mapping of changes in hydrological runoff for the entire Albertine Rift corridor generated by the Lund-Potsdam-Jena (LPJ) dynamic vegetation model run with downscaled multi-model inputs. **b (left)** Changes in means calculated all grid cells within the Nyungwe-Kibira sub-region of the Albertine Rift for Annual Total Runoff and **c (right)** Actual Evapotranspiration relative to 1990 historical baseline from LPJ model simulations in 2030, 2060 and 2090 under the A2 emissions scenario.

Carbon and Fire

The LPJ model contains output parameters for biomass carbon pools and fluxes, for which the one of greatest relevance to the characterization of future climate impacts in the Nyungwe forest biome is the fire parameter. The carbon pools are important for assessing carbon sequestration function over time, with important implications for climate change mitigation efforts through carbon management, for example, REDD/REDD+ programs (Nsabimana 2009). The fire parameter projects the amount of carbon lost to fire per unit area per year as an indication of desiccating climatic stresses upon vegetation: actual ignition is dependent upon either natural (lightning) or anthropogenic factors. In the predictions under the A2 scenario, the total carbon in the Nyungwe-Kibira landscape remains relatively invariant throughout the century (Figure 4.5a). The fire parameter initially follows this pattern (Figure 4.5b), and then exhibits a 10% drop between the last periods of the century, presumably the result of the reduced potential for desiccation as precipitation increases intensify in the latter part of the century. However, a more subjective perspective suggests that over the next several decades, mid-year burning is likely to intensify due to rainfall decreases during the dry season, exacerbated by concomitant warming-enhanced seasonal desiccation of vegetation.

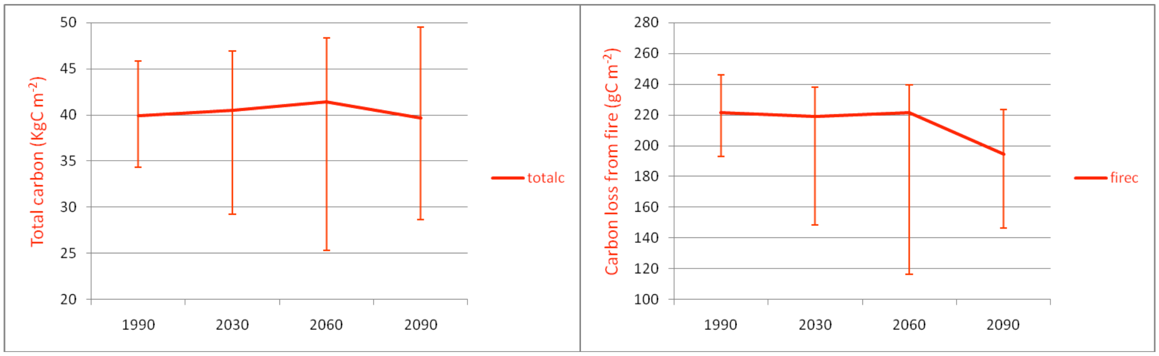

Figure 4.5: a (left) Total Carbon (kgC m-2) and **b (right)** Carbon Loss from Fire (gC m-2) relative to 1990 historical baseline from LPJ model simulations for 2030, 2060 and 2090 under the A2 emissions scenario.

Plant Functional Type

The Plant Functional Type (PFT) parameter is a characterization of the fractional coverage in model grid cells of vegetation according to simple classes as assessed by the LPJ model. The version of the model utilized for this study features 10 PFT classes, over which three are represented in significant fractions in the Nyungwe-Kibira landscape (Figure 4.6). The dominant class is tropical broadleaf evergreen forest (*trbe*), with small fractions of tropical broadleaf raingreen forest (*trbr*) and C4 grasslands (*c4pg*). Under the A2 scenario little change is projected in fractional coverage for any of these classes, other than an early gain in *trbr* at the expenses of *trbe*, which reverse in the last time period. A continued strong dominance of tropical broadleaf evergreen trees would suggest that the current forest would remain extant through the end of the 21st century, despite the large magnitude changes in climatic conditions predicted.

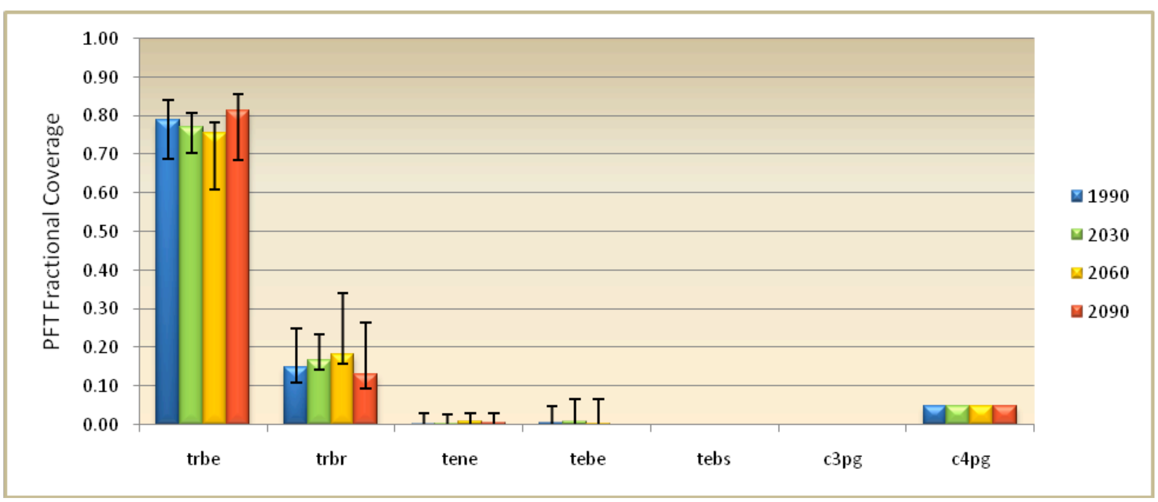

Figure 4.6 Fractional coverages of seven Plant Functional Type classes in the Nyungwe-Kibira landscape as represented by the Lund-Potsdam-Jena dynamic vegetation model under the A2 scenario for the baseline year 1990 and in simulations for 2030, 2060 and 2090.

Agriculture

As a proxy indicator of human response to the climatic changes generated in climate model predictions, the WCS Climate Assessment modeling study also generated predictions of the potential distributions and changes over time of three cultivars of regional importance in Albertine Rift socioeconomic contexts. These are Maize, Phaseolus Beans, and a native pasture grass, *Brachiaria decumbens*, which is highly palatable to livestock and considered a strong indicator of pastoral livelihoods. Spatial mapping of potential distributions of each cultivar, and plots showing changes in predicted yield for the Nyungwe-Kibra sub-region, are presented in Figure 4.7. The results vary considerably. The potential crop yields for Bean are relatively stable throughout, while Maize increases by 9% through 2090. In marked contrast Brachiaria forage rises rapidly, with yields by 2090 rising by 62% above the 1990 baseline. The mapped results show that the central region of the Albertine Rift, centered on Rwanda and Burundi and the Nyungwe-Kibira landscape encompassed therein has favorable yield outcomes relatively to most of the rest of the Albertine Rift.

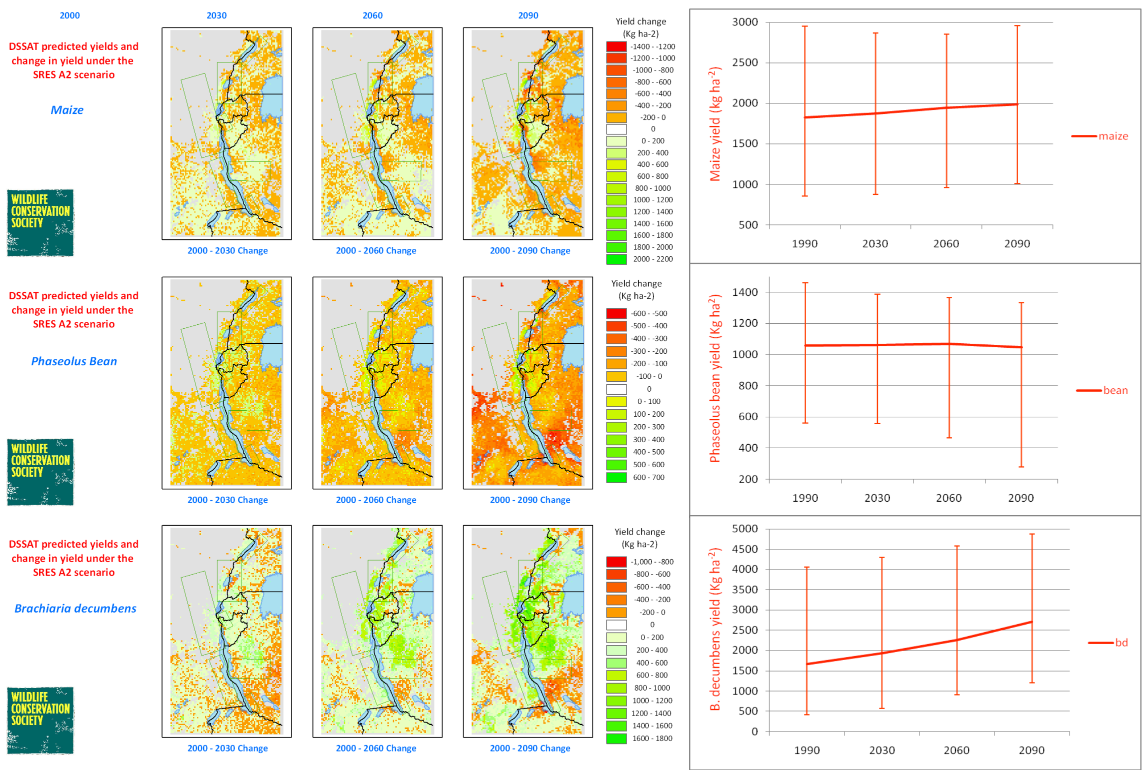

Figure 4.7 Predicted yield changes (in kg per hectare) of three key cultivars for the 21st century under the SRES A2 emissions scenario generated by the WCS Albertine Rift Climate Assessment project. **a** (**top row**) Maps show change in yield for maize relative to the 2000 in 2030, 2060 and 2090 for entire Albertine Rift modeling domain. The graph at right shows the trend for the Nyungwe-Kibira subsection alone. **B** (**middle row**) Similar plots for Phaseolus beans; and **c** (**bottom row**) for the pasture grass ***Brachiaria decumbens.***

5. CESM products for Nyungwe

The second set of model outputs examined here is from the CESM, a fully integrated modeling system under development for almost two decades yet which, to our knowledge, has not previously been utilized to inform vulnerability assessments of conservation landscapes in Africa.

The CESM is a fully coupled system linking atmospheric, oceanic and terrestrial processes directly, and thus can capture feedbacks. This brings it closer to representing real-world conditions and dynamic change processes than many other models, though as with any predictive model offering projections of the future the CESM inevitably is constrained by how well its initialized state can capture real-world conditions. It also represents a newer generation of model products being part of the suite of GCM outputs developed for the CMIP5 series that are serving as inputs to the IPCC's Assessment Report 5 (AR5), due for release in 2013. In addition to the advantages gained over time in refinements in model processes and more powerful computational resources, the CMIP5 models have the distinct advantage over CMIP3 simulations in being initialized ~5 years further into the anthropogenically modified future, and thus anthropogenic global change forcings are stronger and more readily discernible from background states.

Modeling approach

The CESM is a fully-coupled model for the Earth System, which for purposes of climate predictions is run with climate forcing prescribed through annual changes in land cover, solar irradiance, greenhouse gas concentrations (CO_2, CH_4, N_2O, O_3, CFCs), natural and anthropogenic aerosol burden, and aerosol (black carbon and dust) and nitrogen deposition, as described in Gent et al. (2011). The modeled products presented here are derived from the CESM's atmospheric model, the Community Climate System Model version 4.0 (CCSM4) and the terrestrial model, the Community Land Model version 4 (CLM4). The output utilized in the analysis presented here was generated globally at ~1 degree spatial resolution in the NCAR CCSM4.0 fully coupled climate simulations run in the CMIP5 project. The products examined for the Nyungwe region involve land cover change, land surface climate, and changes in the terrestrial carbon cycle.

The CMIP5 climate simulations of the CESM were run as a series of five fully transient time series, and are described in Lawrence et al. (2012). The first simulation is the Historical run from 1850 through 2004, which incorporates known radiative forcings such as greenhouse gas emissions, land surface changes, volcanic eruptions, aerosol emissions. This simulation of the recent past then leads to four Representative Concentration Pathway (RCP) future scenarios that extend from 2005 to 2100. Each RCP has a unique land cover change and climate trajectory, with the RCPs spanning a wide range of radiative forcings at the end of the 21st Century spanning 2.6 W/m^2 to 8.5 W/m^2.

For Nyungwe National Park the changes in land cover, climate, and carbon cycle for each simulation have been extracted for a single 0.9 x 1.25 degree grid cell centered at latitude -2.356, longitude 28.75. This point is located southeast of Nyungwe in Burundi, but the grid cell fully encompasses Nyungwe National Park and the surrounding region with land surface representation generated from higher resolution data (0.05 degrees, or approximately 5.5 km grid cell resolution), as shown in Figure 5.1. Since the analysis covers one grid cell only, the model outputs are not spatially mapped in the products presented hereafter in this section.

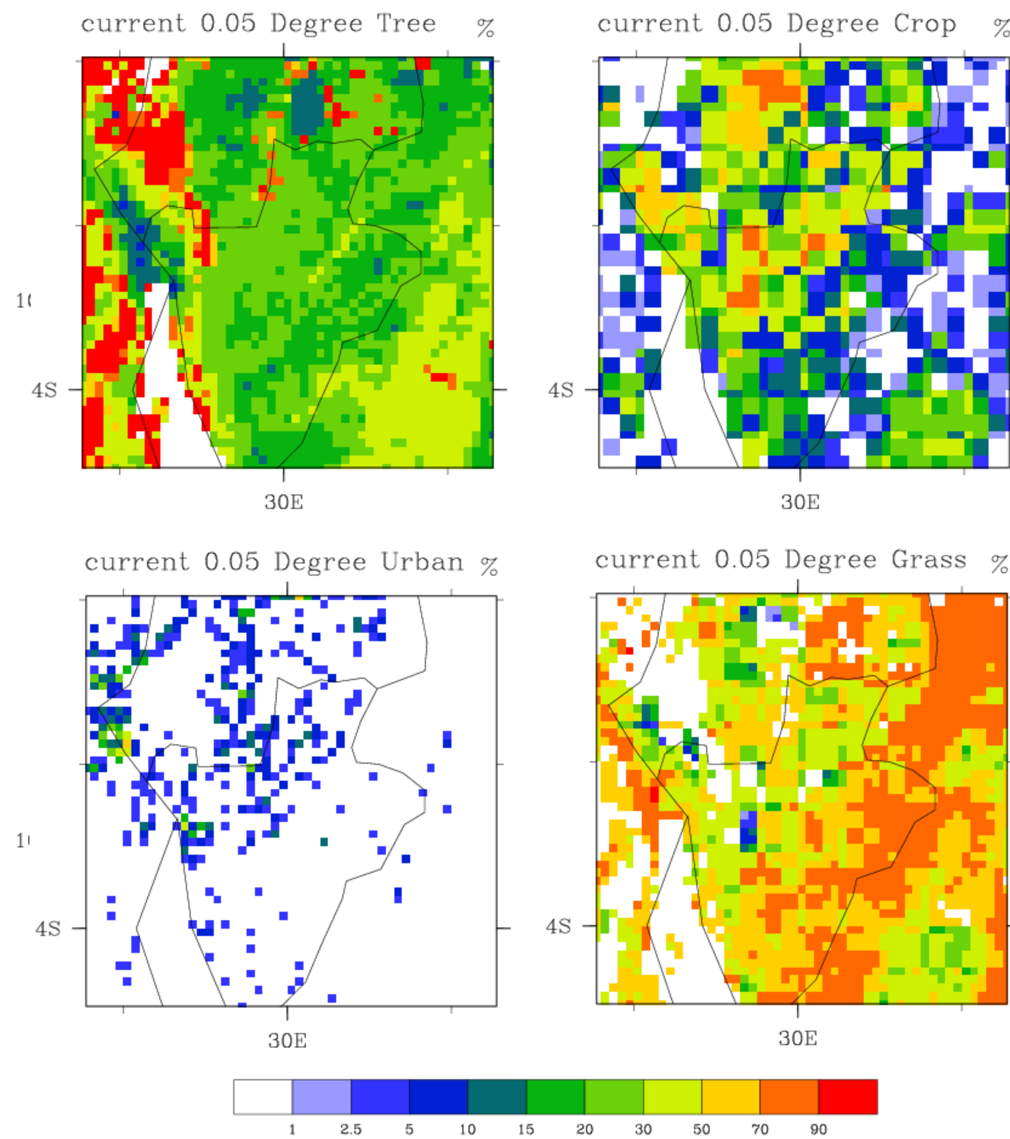

Figure 5.1: Land cover representation (percent coverage) in Community Land Model version 4 (CLM4) within the 0.9 x 1.25 degree lat-lon CESM pixel assessed in this study for **a**: Tree (top left); **b**: Crop (top right); **c**: Grass (lower right) Plant Functional Types (PFTs) and **d**: Urban (lower left) for the year 2000. Thin lines show national boundaries centered on Burundi with Rwanda at upper center, Tanzania on tight and Democratic Republic of Congo on the left. Red and orange shading indicates high degrees of coverage; white and blue shading indicates little if any coverage. The Nyungwe Forest landscape lies in southwest Rwanda, and is evident in the depiction of tree cover >90% and grass cover <1%. Figure provided by Dr. Peter Lawrence, National Center for Atmospheric Research (Boulder, Colorado, USA) NCAR.

Model outputs

Evaluation of CESM representation of current state of Nyungwe and environs

The CLM4 spatial coverage of the various land cover classes shown in figure 5.1 demonstrates that the model offers relatively good representation of the presence of the Nyungwe forest and some of its key characteristics. Tree coverage is portrayed as being over 90% for most of the park, whereas coverage of crops, urban areas and grasslands are minimal (refer to the satellite image in figure 1.1 for comparison).

These patterns effectively invert at the approximate locations of the park boundary, which although not explicitly mapped for this analysis but can easily be inferred from the spatial patterns. The CLM4 model's representation of the land surface therefore suggests a much better approximation of actual conditions than that of the other modeling approaches described above. On the other hand, with the model run at coarse resolution the potential for utilizing such detail in spatially explicit simulations is not realized.

A large suite of standard CESM outputs has been provided by NCAR for the Nyungwe region grid cell, covering 14 climate variables, 9 carbon pool variables, 8 carbon fluxes and 6 out of 15 possible PFTs (the other 9 are not present in the grid cell) (Table 4). These product sets are available for the Historical run and for each of the four RCPs. Comprehensive evaluation comparing the outputs generated by the different RCPs is beyond the scope of the present study, which is primarily concerned with evaluating the utility of model outputs to address questions on climate change consequences to biodiversity conservation. However, it is important to keep in mind that modeled variables such as PFTs are offer approximations based upon partial understanding, given that the relationship of climatic variables to individual plant functional types is not well established. Furthermore, the land cover changes under the RCP projections are prescribed according to global patterns, and therefore are unlikely to represent the particular land use-land cover change characteristics of the Nyungwe region. For further details please refer to the descriptions on land surface characteristics under the four RCP simulations in Lawrence et al. (2012).

TABLE XX: CESM Output variables available for the Nyungwe-area study	
Products available for the 0.9 x 1.25 degree grid cell centered at latitude -2.356, longitude 28.75.	
	Climate variables (monthly)
Albedo:	Fraction of incident broadband solar radiation reflected (0-1)
2m Temp:	Two meter reference height temperature (Kelvin)
LAI:	Leaf Area Index (m^2/m^2)
Precip:	Precipitation (mm/day)
SWR:	Shortwave Radiation Absorbed (W/ m^2)
LWR:	Net Longwave Radiation out of surface (W/ m^2)
Sensible:	Sensible Heat Flux out of surface (W/ m^2)
Latent:	Latent Heat Flux out of surface (W/ m^2)
Ground:	Ground Heat Flux into soil (W/ m^2)
Transpiration:	Transpiration from plants (mm/day)
Canopy Evap:	Canopy Evaporation of intercepted precip. (mm/day)
Soil Evap:	Soil Evaporation (mm/day)
Runoff:	Surface Runoff (mm/day)
Drainage:	Deep Soil Drainage (mm/day)
	Carbon pools (monthly)
Ecosys Carbon:	Total Ecosystem Carbon, excluding product pool (gC/m^2)
Product Pool:	Product pool from wood harvest for long term decay (gC/m^2)
Leaf Carbon:	Leaf Carbon (gC/m^2)
Wood Carbon:	Wood Carbon including coarse roots (gC/m^2)
Root Carbon:	Fine Root Carbon (gC/m^2)
Storage:	Stored non Structural Carbon (gC/m^2)
CWD:	Coarse Woody Debris Carbon (gC/m^2)
Litter:	Leaf and Root Litter Carbon (gC/m^2)
Soil Carbon:	Soil Carbon (gC/m^2)
	Carbon fluxes (monthly)
NPP:	Net Primary Production ($gC/m^2/day$)
Land Use:	Land Use Flux ($gC/m^2/day$)
Het Resp:	Heterotrophic Respiration ($gC/m^2/day$)
Fire:	Fire Flux ($gC/m^2/day$)
NEE:	Net Ecosystem Exchange ($gC/m^2/day$)
GPP:	Gross Primary Production ($gC/m^2/day$)
Harvest:	Wood Harvest Flux ($gC/m^2/day$)
Sink:	Residual Terrestrial Sink Flux ($gC/m^2/day$)
	Plant Functional Type (annual)
PFT4	Broadleaf Evergreen Tree – Tropical (km^2)
PFT5	Broadleaf Evergreen Tree – Temperate (km^2)
PFT6	Broadleaf Deciduous Tree – Tropical (km^2)
PFT13	C3 Grass (km^2)
PFT14	C4 Grass (km^2)
PFT15	Crop (km^2)

The temporal evolution for several key variables under the retrospective CCSM4 Historical simulation (1850-2004), merged sequentially with output from the forward-looking RCP8.5 simulation (2005-2100) will be the focus of this analysis. With the highest radiative forcing changes of the RCP suite, RCP8.5 consequentially exhibits the highest degrees of change for many of the variables. The emissions trajectory of RCP8.5 generally follows the SRES A2 scenario presented in the modeling studies presented above. Annual cycles in temperature and precipitation for the four RCPs for the year 2100 and 1995, representing a contemporary baseline year, are compared in Figure 5.2.

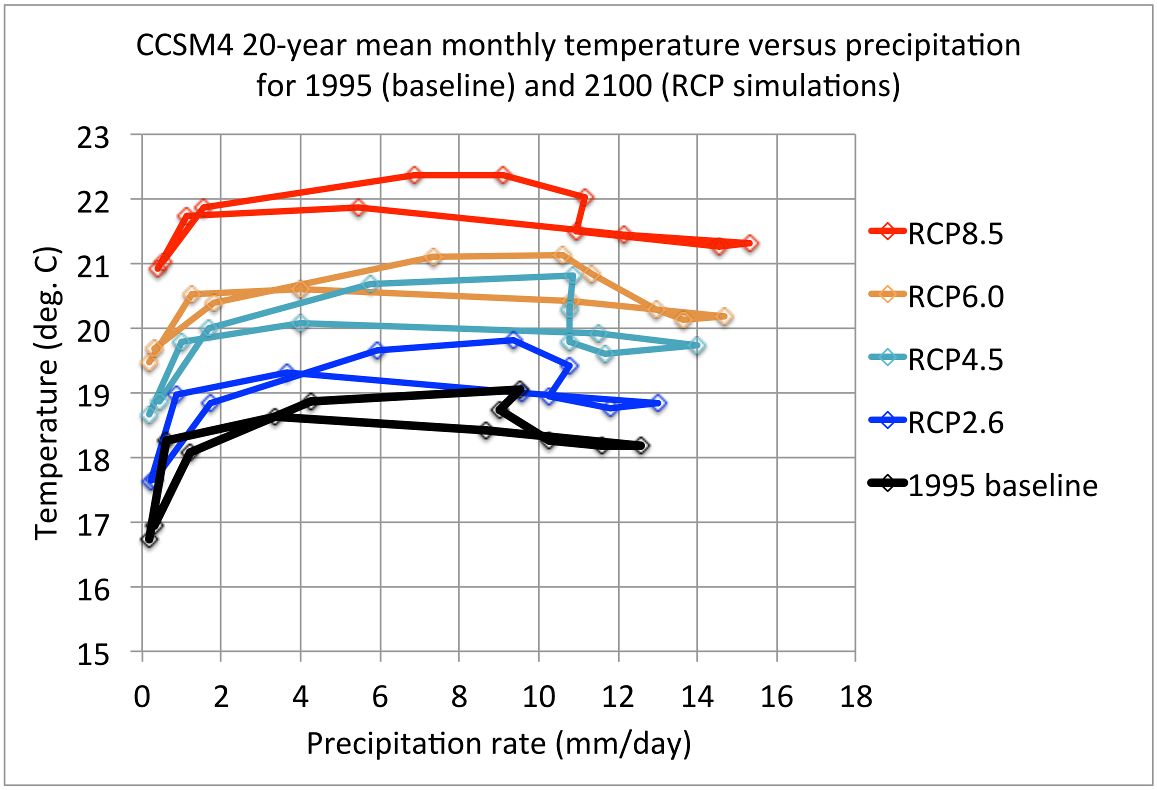

Figure 5.2. Monthly mean temperature (°C) plotted against precipitation rate (mm/day) in CCCSM4 output in the Nyungwe-area grid cell for 20-year periods covering 1985-2005 (Historical simulation) and 2080-2100 (Predictions), for each of the four greenhouse gas Representative Concentration Pathway (RCP) simulations.

Model trends of climatic conditions

The principle variables of mean temperature and precipitation amount are available at monthly intervals for the period 1850-2099; following convention, values ascribed to individual years are 20-year averages centered on the given year to better represent decadal trends from statistical noise associated with transient short-period phenomena such as El Nino events and volcanic eruptions. The overlap with observational records is quite small for the reasons described in section 4, and direct comparison is problematic given the large extent of the grid cell for which Nyungwe covers just a small fraction. Nevertheless, the trends in temperature appear to be consistent with patterns from regional observations (Seimon and Picton Phillipps, 2012) and observations documented more broadly across eastern Africa (Seimon et al, in press). Monthly mean temperatures are portrayed as cool and relatively stable for the period 1880-1970, with a rapid rise thereafter and already evident by 2000 (i.e. 1990-2010) (Figure 5.3). The 40-year thermal trend reported in the Oxford University study identifying an increase of 0.35°C per decade appears to be consistent with the CCSM4 outputs. In the RCP8.5 simulation temperature increases are projected to continue at an accelerating pace for the remainder of the century, reaching 0.45°C per decade for the period 2060-90. Increases occur relatively uniformly for all months of the year, and despite the large changes in magnitude the thermal seasonality pattern is therefore maintained across the entire period. In contrast, precipitation trends and seasonality differ markedly from those exhibited in the temperature output. In the CCSM4 hindcast and RCP8.5 projections the seasonal cycle is weakly bimodal in most of the time steps, but the relative proportion of precipitation falling early versus late in the hydrological year becomes highly asymmetric, with Oct-Dec becoming much wetter than in the recent past while the Feb-April Long Rains period exhibit much smaller increases.

Climate envelopes representing both parameters are plotted relative to one another in Cartesian space for a set of years for the Nyungwe Historical hindcast and RCP8.5 forecast in Figure 5.3 (lower panel). In this display polygons yielded by the annual pattern of temperature vs. precipitation retains their general form while lifting vertically, representing the relatively monotonic increases in temperature, while also expanding significantly to the right, indicative of large increases in early wet season precipitation.

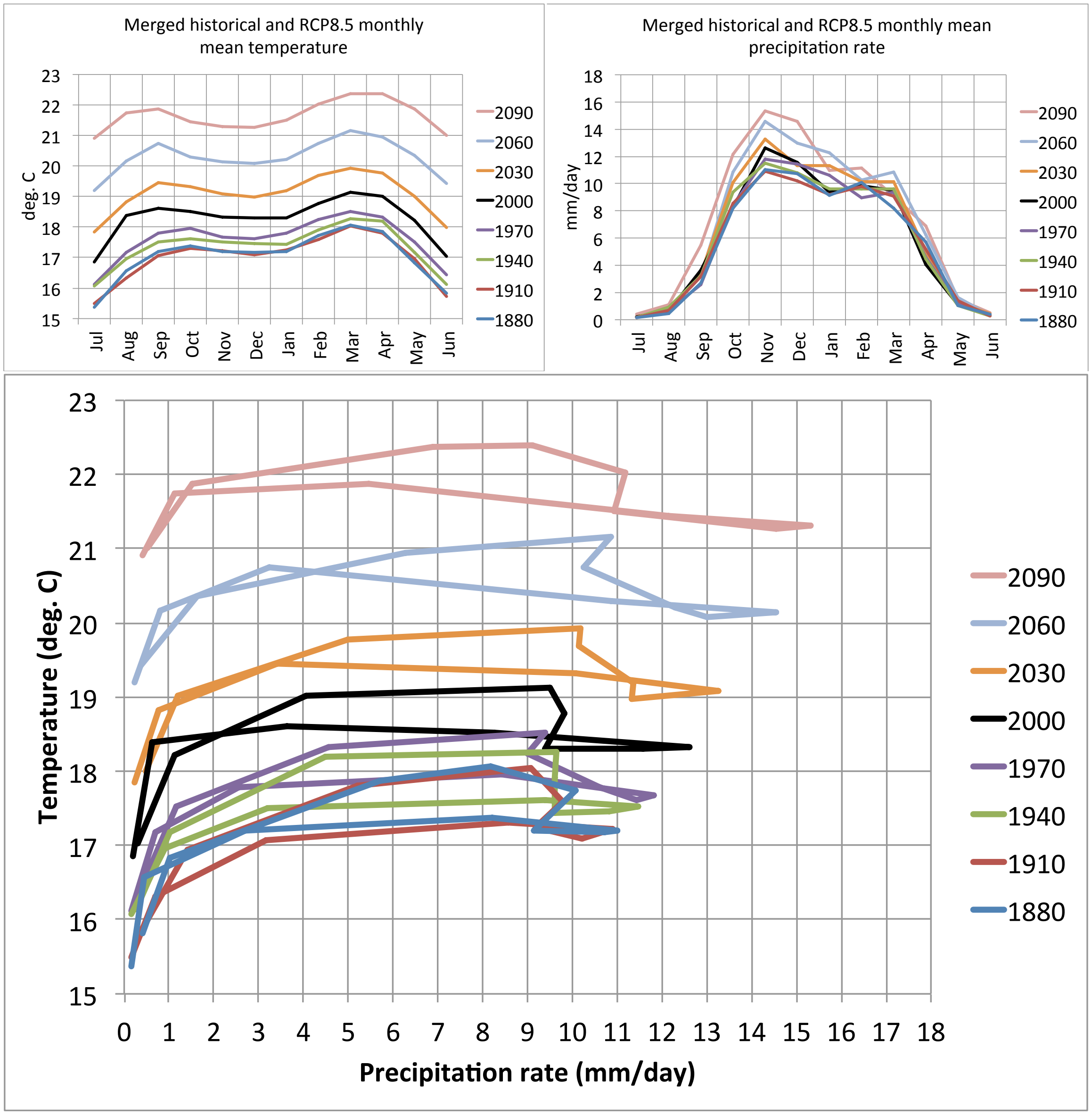

Figure 5.3. Mean monthly temperature (degrees C) (**upper left**) and precipitation rate (mm per day) (**upper right**) in CCSM4 simulations for the Nyungwe region for 20-year periods at intervals of 30 years for the period 1880-2090, based on the Historical CMIP5 run (to 2004) and thereafter under the RCP8.5 emissions and land use scenario to 2100. These results are plotted against one another as climate envelopes for corresponding months and years (**bottom**).

Hydrology

The CESM output apportions all precipitation received in the grid cell space to a set of hydrological output mechanisms. Evapotranspiration is assessed according to its components in plant transpiration, canopy evaporation and soil evaporation, while runoff and deep soil drainage serve as inputs to terrestrial hydrology. These are shown for the 1850-2100 simulation period for the individual and combined components in Figure 5.4. These results suggest that deep soil drainage (percolation) is a highly volatile parameter, with far greater variance and trend behavior than the other hydrological fluxes. The evaporative fluxes show only modest variability and trends, which is somewhat surprising given 20th century deforestation and other land use changes captured in the model.

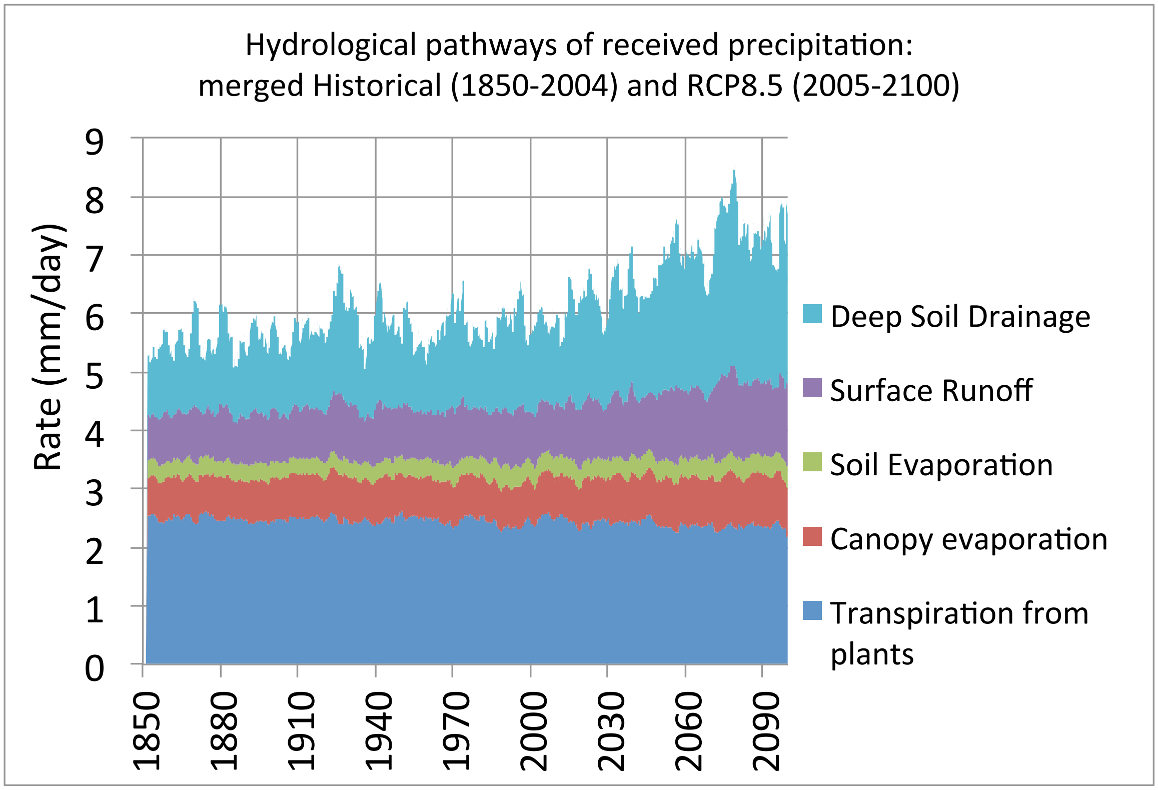

Figure 5.4. Cumulative annual profiles of outgoing hydrological components of received precipitation for the Nyungwe-area grid cell for the years 1850-2100, as projected by the CESM Historical and RCP8.5 simulations.

It is noteworthy that in the model's projections, the large increase in precipitation in the 21st century is allocated primarily to groundwater through deep soil drainage, with surface runoff showing relatively modest gains only mostly in the latter half of the century. If borne out, such patterns would have important implications for the provision of hydrological services to human interests such as irrigation, water quality and hydroelectric power generation, as well as to geohazards phenomenology of landslides and flood events. In the CESM's hydrological pathways, both the deep soil drainage and runoff parameters feed into the River Transport Model (RTM), which is a drainage model that flow water the land grid cells to the ocean (P. Lawrence, personal communication). Therefore, the deep soil drainage does eventually feed streamflows, but represents a delayed release compared to the rapid response registered by direct runoff. (The RTM results yielded by the outputs shown in Figure 5.4 were not available for this analysis).

The shifting proportion of precipitation directed to runoff and percolation, if this can be demonstrated to be likely, could likewise have implications in national and local-level planning. Nyungwe's importance for dry season river water provision is well recognized (Chao et al., 2012), and is a fundamental rationale underlying the park's creation and long-term prospects for preservation. The early and late season precipitation trends and corresponding runoff and drainage responses under the historical and RCP8.5 simulations for the Nyungwe-region grid cell are shown in Figure 5.5 respectively. This reveals that under the modeled conditions there is little immediate runoff response, whereas groundwater recharge, as indicated in the deep soil drainage flux parameter, exhibits responses approximately in proportion to the precipitation trends both early and late in the season.

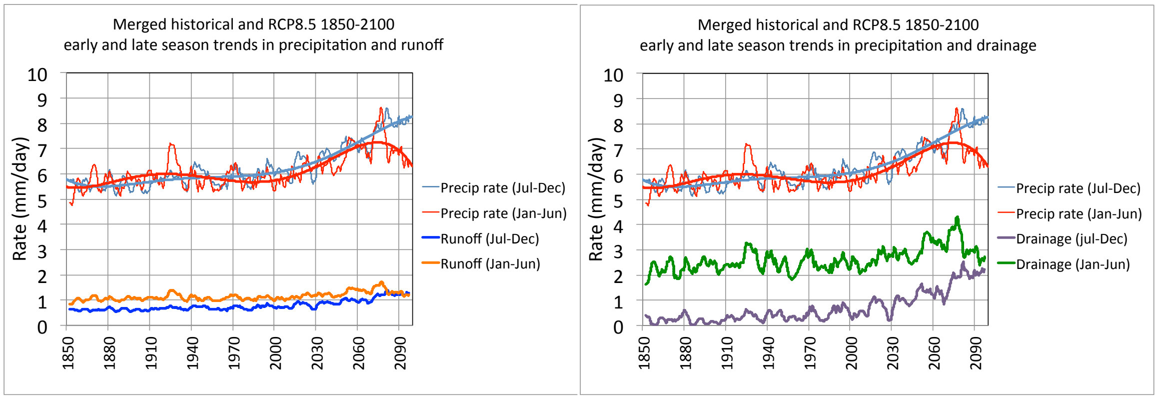

Figure 5.5. Early and late wet season precipitation rates compared to corresponding runoff (**left**) and deep soil drainage (**right**) in the merged Historical and RCP8.5 simulations for the Nyungwe-area grid cell. The precipitation data is overlaid with polynomial curves to facilitate identification of multi-decadal trends in the model output.

The increased percolation implies possibly increased the leaching of minerals and nutrients from soils, and sediment transport due to increasing base flows in waterways. This also suggests that groundwater withdrawals may serve as a highly effective adaptation measure to support agriculture during the desiccating midyear dry seasons that will likely intensify under the rapidly warming climate. For Nyungwe, such guidance may also serve to counter arguments that building reservoirs in highland catchments, of which the Kamiranzovu Swamp is already among recognized targets, is the optimal strategy to ensure dry season hydrological provision for the rest of the country. Such assertions are merely conjectural when based upon coarse resolution model output: regional modeling conducted at high spatial resolution (i.e. 1-5 km grid cells) would therefore be a significant asset towards properly informing national level decision makers and conservation planners.

Vegetation dynamics

The CLM4 products for vegetation offer greater versatility and precision than was available for the LPJ simulations conducted for the WCS Climate Assessment project in 2007. These improvements are evident in the Nyungwe region grid cell products, and particularly so in the PFT evolution for the 20th century leading to the baseline conditions shown in Figure 5.1 above. The Historical simulation offers a depiction of the widespread conversion of tropical forest to agricultural lands developed from observational data, where PFT15 representing all cropped surfaces increase more than five-fold over the 90-year period ending prior to the 2005 transition point between the CLM4 hindcast and forecast (Figure 5.6). This occurs primarily at the expense of PFTs 4 and 5, which represent lowland and afromontane forest respectively. In the post 2005-projections the cropland extent stabilizes at current levels yet forests continue to contract, albeit more slowly than during the 20th century. These losses are balanced by increases in C3 grasslands. Whether this represents a response to anthropogenic factors such as deforestation for wood harvest and/or to increase livestock pasturage, or alternatively, forest dieback and replacement with grasslands in response to greenhouse gas driven climatic forcing, cannot be determined from the information provided.

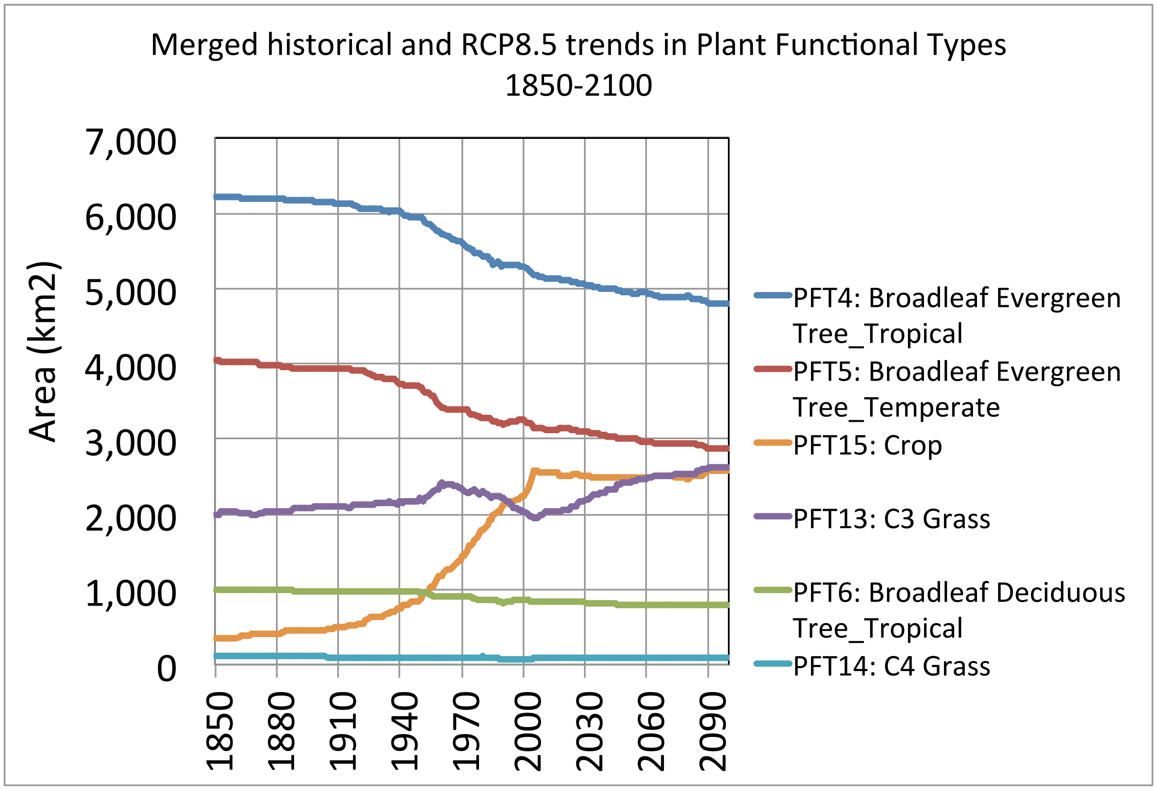

Figure 5.6. Time series for the six Plant Functional Type classes present in model output for the Nyungwe-area grid cell in the merged Historical and RCP8.5 simulations.

Carbon pools and carbon fluxes

The CLM4 output offers a relatively complete accounting of ecosystem carbon on a monthly basis for a comprehensive set of component carbon pools. The time series trends for the merged Historical and RCP8.5 sequence of the various carbon pools are presented in Figure 5.7. The most significant event occurs in the Historical time series, when the widespread deforestation of the 20th century resulted in severe depletion of wood carbon, with more than 80% of the stock removed by the cessation of the deforestation trend around 1995. In the model's portrayal less than 50% of ecosystem carbon presently exists relative to the 19th century pre-colonial period, before forest conversion to agricultural land become widespread in the region. In the post-2005 projections in the RCP8.5 simulation total ecosystem carbon continues to decline, due primarily to a decline in soil carbon content, which decreases linearly throughout the time period. The causality driving this decrease cannot be determined, though may possibly relate to increasing rates of heterotrophic respiration under the warming climate regime.

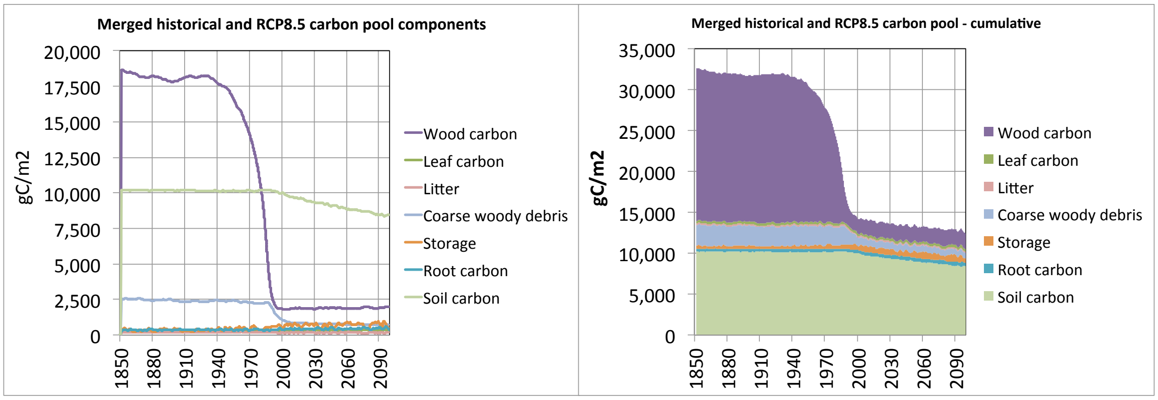

Figure 5.7. Trends in individual (**left**) and cumulative carbon pool components (**right**) for the CLM4 grid cell encompassing the Nyungwe Forest for the time period 1850-2100.

Trends in carbon fluxes can be similarly plotted to ascertain changes to individual components and their cumulative trends (Figure 5.8). In these depictions the anthropogenic land surface conversions of the late 20th century initiated a completely different carbon flux regime than the period that preceded it, and the RCP8.5 simulation sustains the new regime through 2100. Significantly, the widespread deforestation and land use changes are shown to have precipitated an abrupt transition of the grid cell domain from a weak carbon sink to source.

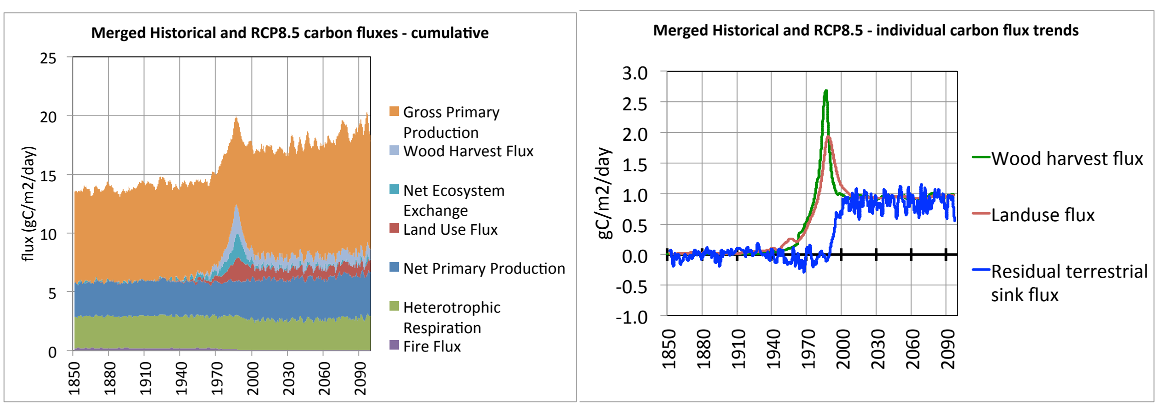

Figure 5.8. (**left**) Time series for the cumulative carbon flux components in model output for the Nyungwe-area grid cell in the merged Historical and RCP8.5 simulations. **(right)**. Time series of individual carbon flux components demonstrating the relationship between land use and wood harvest and the transition of the landscape encompassed by the grid cell from weak carbon sink to carbon source.

The model's portrayal of the temporal evolution of ecosystem carbon fluxes with the Nyungwe-area grid cell demonstrates the severe anthropogenic disturbances and legacy of landuse change for the multicountry region during the mid-late 20th century. In this portrayal fire is shown to be a relatively negligible factor in carbon exchange dynamics. However, the carbon flux parameter for fire as generated in the merged Historical and RCP8.5 simulation appears to be poorly suited for informing fire management planning in Nyungwe. In the simulations, fire frequency is maximized in the June-August dry season months, and the time series of carbon flux from fire for these months for each year between 1850-2100 is presented in Figure 5.9. This reveals that in the modeled environment fire was a significant factor though of low magnitude under the pre-colonial land cover regime, when tropical lowland and afromontane forests dominated the grid cell region. The widespread deforestation and landscape conversions that ensued during the 20th century greatly reduces the carbon flux from fire incidence, with the 21st century characterized by a stable pattern similar to that experienced in the present day. While this may reflect aspects of reality across the broad region encompassed by the grid cell, it is an extremely poor analog for known fire behavior in the Nyungwe Forest as described in section 3.

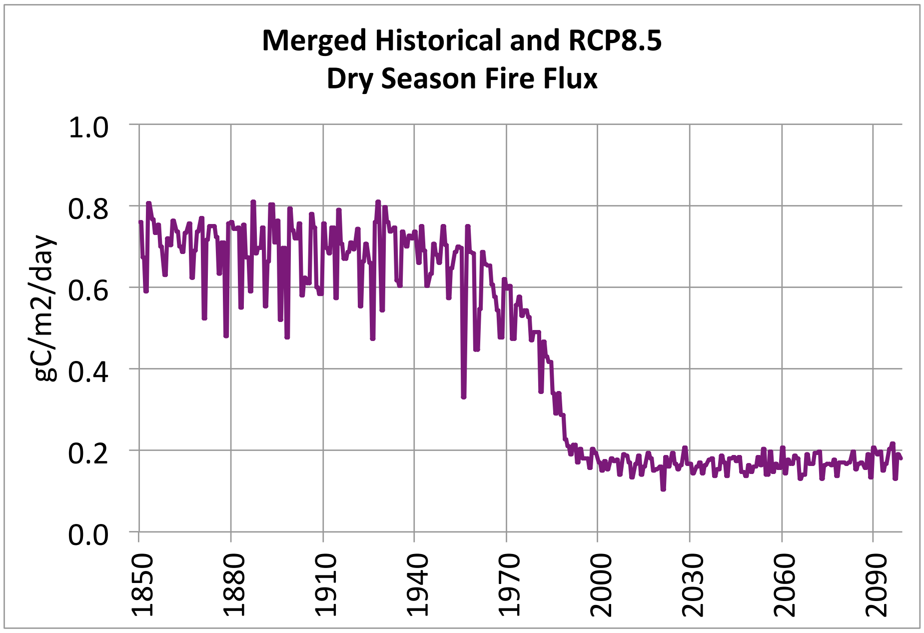

Figure 5.9. Time series of carbon flux from fire averaged for the Jun-Aug dry season months in model output for the period 1850-2100 I the Nyungwe-area grid cell for the merged Historical and RCP8.5 simulations.

How well CESM grid cell data applies to Nyungwe's climatology is difficult to ascertain given the coarse resolution of the model in the CMIP5 simulations. The hydrological rainfall accumulations and monthly distributions shown in this section are quite different to those shown in the Uwinka data, but this could reflect local climatic behavior around Nyungwe, which as a high elevation mountain forest is likely to have distinct climatology that differs considerably from much of the landscape encompassed within the grid cell. In particular, the annual precipitation accumulation at Nyungwe is about 10% less than the grid cell value, and the annual hydrological peak is experienced in March, whereas the model shows it in November for all of the time periods considered. Furthermore, both September and May are shown as dry months in the model hindcast leading to the present, while in actuality the Uwinka observation show that September features significant rainfall in most years, and the wet season extends 2-3 weeks into the May before the abrupt cessation highlighted in section 4.

6. Discussion

The analysis presented in this study of site-specific climatology of the Nyungwe Forest, reveals a set of baseline conditions that establishes the contemporary state of the climate and offers indications of climatic trends that may be early manifestations of a changing climate. Such information is critical as real-world referencing with which numerical modeling output of future conditions can be evaluated. The model outputs in turn generate a large number of environmental variables that could be monitored in the real-world setting of Nyungwe, yet very few are as yet observed in any kind of systematic manner.

Representation of climatic trends by models

As described in section 3, although climatological observations within the Nyungwe Forest are severely limited both in duration and data quality, there are already clear indications of significant change trends for both temperature and precipitation at decadal scales. Multiple sources identify that temperatures are increasingly regionally at a rapid rate of approximately one third of a degree per decade, which is in line with climate projections presented here from the A2 scenario for a CMIP3 multi-model ensemble and under RCP8.5 for the CCSM4 simulation produced for CMIP5. The large increase observed since 1996 in annual precipitation is consistent with the simulated climates in both the WCS and CESM outputs many decades into the future, though is strongly at odds with predictions in the near-term. If this pattern were sustained, and thus a product of a change in atmospheric circulation rather than variability within a quasi-table system, it would be occurring far earlier than predicted by any GCM. Attributing causality for such changes is furthermore problematic since climate change at a particular locality is the cumulative product of at least 3 distinct types of forcing mechanisms. These include secular trends, such as warming related to anthropogenic greenhouse gas emissions, changes in the drivers of interannual variability, related primarily to oceanic circulations, and land cover changes, which produce local-regional scales changes (Seimon et al., in press). The CESM outputs tend to suggest that causality underlying the rapid warming in the Nyungwe region most likely relates to the combined effects of secular greenhouse gas forcing and the widespread 20th century landcover transformations. A role of land cover changes in the recent Nyungwe rainfall trend appears unlikely, since anthropogenic landscape conversion of Rwanda's forests to croplands was largely complete by 1996, the start of the period of measurements examined from Uwinka. This implies that the rainfall increases are a product of increase moisture transport to the Nyungwe region, which implies that changes are a response to broader scale circulations across central Africa and the adjacent Indian and Atlantic Ocean basins (see reviews in Giannini et al., 2008 and Seimon et al., in press).

In general, GCM projections for East Africa previously generated from the CMIP3 model suite show fairly consistent results in terms of temperature and precipitation trends for the 21st century (Seimon et al., in press), although, as shown in Figure 1.1, there is still considerable spread among the individual models, and especially so for annual mean precipitation trends when the Rwanda region is examined more specifically. It is therefore encouraging to note that the new CCSM4 simulations are consistent with the older CMIP3 consensus showing a rapidly warming and increasingly wet climate for the region, since this builds confidence that such predictions have foundations in well-understood global oceanic and atmospheric forcings, and should serve as the basis for adaptive conservation and socioeconomic planning for climate change. The model outputs assessed for this study are limited by spatial resolution and uncertainties inherent in numerical climate prediction, particularly, in the unknowable degree of change in the various radiative forcings that are deterministic to climatic states. Both of these factors render the current set of guidance products as informative in a general sense, but still inappropriate if used as specific forecasts to serve as the basis of adaptive planning to address recognized vulnerabilities to climatic stress. The CCSM4 output used for the CESM as evaluated in this study furthermore considers only one RCP out of four available in the CMIP5 modeling suite. A more comprehensive evaluation for Nyungwe's future climatic states should include other RCPs and similar sets of simulations generated by other GCMs.

Model resolution

The applicability of the outputs from both of the modeling systems evaluated in this study for addressing conservation issues, and to guide adaptation planning for climate change for the Nyungwe Forest specifically, is greatly limited by the coarse resolution of the outputs. In the case of the CESM, the grid cell is an order of magnitude larger in area than the park extent. Little inference can therefore be derived, for example, on how changes occur across space within and outside the forest boundaries. The CESM has the capability to be run using a regional climate model (RCM), where a nested domain can be represented at high spatial resolution as refined as $1km^2$, meaning that the 1,013 km2 domain of the Nyungwe National Park would be represented by a comparable number of grid cells, an enormous improvement on the output examined in this study and thus capable of properly representing landscape and climatological heterogeneity. Conducting simulations at this resolution, and ensuring the most accurate inputs of environmental realities into the model components, should provide the level of detail needed to addresses some of the key questions on climate change impacts at Nyungwe and identify possible actions needed to address them. Shortcomings identified in the current output, such as the inability of the model to represent fire trends and risks in the Nyungwe Forest, may well be overcome through such refinements in model resolution.

Monitoring needs

Detection of climate change and its impacts on biodiversity and the biophysical environment of Nyungwe are enabled principally through monitoring activities, if conducted in a strategic and systematic manner. The daily observations from Uwinka are shown in section 3 of this study to be of considerable utility in characterizing climatic baselines and in identifying possible trend behavior. There is an obvious need to improve monitoring of key climate variables in the Nyungwe Forest region, both in terms of the number of observing sites and the accuracy and quality of the measurements. The new automatic weather station installed at Mt Bigugu offers a model that would serve well at other sites in the landscape.

Monitoring of flora and fauna is already performed systematically in Nyungwe and has generated robust datasets over the past two decades. For the most part, these activities were not designed with climate change as a motivating factor though now represent a potentially valuable resource to assess plant and animal species responses to climatic variability and trends. Monthly records of forest tree fruiting and flowering phenology recorded in the Nyungwe Forest since 1996 are currently being analyzed in contexts of climatic conditions at a WCS-led workshop. Due to the large losses suffered in the burning episodes of 1997 and in subsequent years, forest loss from fire is a biophysical process that is now well monitored and the subject of considerable conservation attention. Baseline surveys of amphibians and chameleons, taxonomic groups with especially high susceptibility to climatic perturbations, have been conducted in Nyungwe by the Trento Museum of Natural History in Italy in partnership with WCS and the Rwanda Development Board. These surveys follow a model demonstrated as effective in Madagascar to detect species response to changing thermal conditions by recording species diversity and abundance in plots along an elevational transect (Raxworthy et al., 2008).

Outside the park, changes in agricultural productivity can likewise be an indicator of climatic influences that may affect conservation outcomes in the park. Tea, in particular, is of great importance since as a cultivar unpalatable to wildlife, it offers a highly effective buffer between other croplands and the forest that minimizes human-wildlife conflict from crop raiding. It is also economically important, accounting for 35% of Rwanda's national exports (Chao et al., 2012). Tea also high thermal sensitivity, and only grows in the afromontane zone, so likely has high susceptibility to the warming climate.

Questions on critical climatological issues revisited

Responses to the research questions posed in section 1 are offered below using findings and inferences developed in the climatology and climate and ecological modeling sections of this study.

Q1. Will the Nyungwe forest remain extant for the foreseeable future? Results from both the WCS and NCAR products offer strong indication that the climatic conditions will continue to support afromontane forests where presently found in the highlands of the Nyungwe-Kibira landscape. Predicted trends in Plant Functional Types in the A2 and RCP8.5 scenarios – both of which are among the more anthropogenically modified scenarios in the CMIP suite – indicate stable coverages in the key forest classes through the year 2100.

Q2. Are biome transitions to be expected? Spatial mapping of PFTs in the WCS Climate Assessment results suggests strong stability of the current broadleaf tropical forest in the Nyungwe region throughout the course of the 21st century, despite the large increases in temperature and rainfall evident in the climate projections. This contrasts markedly with the situation not far to the south, where a significant transition from tropical deciduous to evergreen PFT classes is predicted for much of the Lake Tanganyika watershed. The CESM RCP8.5 simulation output for the grid cell encompassing Nyungwe suggests a slow decline of forest cover with replacement almost exclusively by C3 grassland. Whether this reflects projections of anthropogenic land use changes in the model or greenhouse gas induced climatic changes, or if this pattern is at all relevant to Nyungwe, is not possible to ascertain given the coarse spatial resolution.

In the vertical dimension, biome shifts and species range extensions are a likely if inevitable consequence of the rapid climatic warming. 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 3-4°C by 2100 under both the A2 scenario and RCP8.5 would translate to a very large upward displacement of thermally-constrained species ranges and vegetation zones, on the order of 600-720 meters relative to 20th century baseline conditions (Seimon and Picton Phillipps, 2012). Precedence for such changes is amply evident in paleobiological indicators (Chen et al., 2011). Given the rapid temperature increases already being recorded, early indications of species responses through range shifts and behavioral changes should be detectable through systematic monitoring along elevational gradients.

Q3. How will agricultural activity bordering the park change, and what are potential consequences of those changes? The WCS crop modeling results suggest that the afromontane zone will experience inexorably increasing pressure to convert forested landscapes for agriculture. This would be driven by both push factors, from the decline of productivity in lowland regions where climatic conditions are predicted to trend unfavorably for agriculture, and pull factors, whereby the afromontane region will become even more productive under the warmer and wetter climate. In addition to this, a significant vulnerability concerns the long-term sustainability of tea as a buffer zone crop. None of the models evaluated consider this cultivar specifically, although a study incorporating climatic sensitivity of tea varietals grown around Nyungwe with predicted climatic changes could address this directly.

Q4. Is the current intensifying fire regime indicative of a trend or variability? The WCS fire and climate products developed from the A2 simulations are informative in addressing this question, and identify that fire frequency and intensity are likely to intensify for the next several decades before rainfall increases reverse the trend. The CESM climate parameters are consistent with this scenario, yet its fire products does not represent the elevated dry season burning potential already present in Nyungwe. The reasons for the increasing dry season desiccation potential to not translate to concomitant increase in fire occurrence should be investigated.

Q5. Is Nyungwe's long wet-season season splitting into two distinct parts, matching the bimodal rainfall pattern currently experienced nearby to the north? It is evident that Nyungwe lies precisely on the margin between two of the Albertine Rift's principal climatic zones in terms of rainfall modalities, and thus is highly susceptible to crossing a tipping point as climate change factors increasingly perturb the regional climatology. None of the model output specifically indicates the development of a dry season in the Jan-Feb period, but higher resolution modeling would be required to resolve the boundary between unimodal and bimodal rainfall regimes and to track its shifting position as a function of time.

Q6. How will the magnitude and relative proportion of early and late season rains change?

Here both sets of model output yield strong indications that early season precipitation will increase markedly, and shift the current modal peak from March to November.

Q7. How will hydrological release from the Nyungwe Forest during the dry season, critical for Rwanda's agriculture and hydropower, develop over time in response to climate change?

The model outputs suggest a lagged response in hydrological runoff to the precipitation increases projected for the 21st century. The CESM output in particular suggest that a large fraction of the increased rainfall receipt will be taken up as deep soil drainage rather than runoff, providing a lagged release of the higher overall streamflows.

Q8. How will the carbon sequestration potential of the landscape change as climatic conditions and atmospheric CO2 levels change?

This can be inferred in a general sense from the time-step outputs of the A2 multimodel simulations, though is far more developed and amenable to examination in the longer-term and continuous CESM time series as shown in Figs. 5.7 and 5.8. The Historical CESM outputs suggest that deforestation and other land use changes have largely eliminated the carbon sequestration functioning for the grid cell region, which now acts as source rather than sink for carbon.

Q9. How will climate change influence natural hazard occurrences in the landscape?

The large increase in hydrological flux into the subsurface suggests significantly increased potential ground saturation to cause slope destabilization that would promote landslides and other mass movements in complex terrain. Given the mountainous character of the Nyungwe landscape, this could become a severe problem if the intensified rainfall and deep soil drainage patterns evolve as indicated. More intense short-period rainfall would also increase flash-flood potential, with greatly increased scouring and sediment transport among the consequences.

Recommendations

The findings on climatology and potential environmental changes in the Nyungwe Forest resulting from global climate change presented in this study bring to light a series of critical knowledge needs for effective adaptation of current conservation planning to accommodate climate change. The following are some recommendations for applying these findings and further developing the analysis and data resource base.

1. Develop a network of meteorological and ecological monitoring sites distributed throughout the Nyungwe Forest utilizing strict observational protocols and instrumentation meeting international standards.
2. Determine whether the strong precipitation increases registered since 1996 in Nyungwe are consistent with or contrary to climate model projections. The regional atmospheric circulation behavior underlying the rainfall increases, and the global forcings that drive them should be identified and related to model outputs to better understand if the models are significantly in error or not. This objective might be informed by conducting a study on the air transport trajectories associated with precipitation events recorded in the Uwinka data series, which can be analyzed for linkages to known global climate forcings and trends (Perry et al., in press).

3. Perform regionally focused simulations to create model output that more properly represent local conditions and portrays changes over time with a sufficient degree of detail across space to inform conservation planning needs. Comprehensive evaluation of key ecosystem services could be conducted with such output, as well as sensitivity studies for cultivars for a series of locally importance subsistence crops such as maize, bananas and potatoes, as well as critically important cash crops such as tea and coffee for inference on how human populations around the Nyungwe Forest may respond to climate change.
4. Increase knowledge base on species response to climate change by examining historical flora and fauna monitoring data for evidence of range shifts related to climate. Given the dependence of temperature upon elevation, determination of the elevation of point observations is a critical need when not explicitly recorded. This could be ascertained if accurate latitude-longitude is available through the utilization of a high-resolution digital elevation model.
5. Design or modify existing monitoring programs to better monitor the changes in climate on species in the park.
6. Create an informational display at the Uwinka Visitor Center in Nyungwe National Park, using findings from this and other studies, to inform the public of Nyungwe's climatology and the potential for climatic change to impacts its flora and fauna.

References

Chao, N, F. Mulindahabi, J. Easton, A.J. Plumptre, A. Seimon, A. Martin and R. Fimbel, (2012) Long Term Changes in a Montane Forest in a Region of High Human Population Density. In, A. Plumptre (Ed.), Long-term changes in Africa's Rift Valley, New York: Nova Science Publishers.

Chen, I-C., J.K. Hill, R. Ohlemüller, D.B. Roy and C.D. Thomas, 2011: Rapid range shifts of species associated with high levels of climate warming. *Science* 333,1024-1026.

Cohen, E., M. Edwardsen, S. McNulty, G. Sun, and M. Wingard, 2011: USDA Forest Service Technical Assistance Africa Program: Project Summary. http://rmportal.net/library/content/translinks/2011/wildlife-conservation-society/final-report-usda-forest-service-technical-assistance-program-project-summary-jan-to-sept-2011/view

Doherty, R. M., S. Sitch, B. Smith, S.L. Lewis, and P.K. Thornton, 2009: Implications of future climate and atmospheric CO_2 content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global Change Biology*, 16: 617–640

Gent, P. R., G. Danabasoglu, L. J. Donner, M. M. Holland, E. C. Hunke, S. R. Jayne, D. M. Lawrence, R. B. Neale, P. J. Rasch, M. Vertenstein, P. H. Worley, Z.-L. Yang, and M. Zhang, 2011: The Community Climate System Model Version 4. *Journal of Climate*, DOI: 10.1175/JCLI-D-10-05011.1.

Giannini, A., M. Biasutti, I.M. Held and A.H. Sobel, 2008: A global perspective on African climate. *Climatic Change*, 90: 359-383.

Ingram, J.C., 2011: Proceedings: Modeling and Managing Watersheds Workshop September 13-16, 2011

IPCC 2000: Intergovernmental Panel on Climate Change. www.ipcc.ch

Kigali, Rwanda. http://rmportal.net/library/content/translinks/2011/wildlife-conservation-society/2011-Watershed-Modeling-and-Management-Workshop-Rwanda

Lawrence, P. J., J. J. Feddema, G. B. Bonan, G. A. Meehl, B. C. O'Neill, S. Levis, D. M. Lawrence, K. W. Oleson, E. Kluzek, K. Lindsay, and P. E. Thornton, 2012: Simulating the Biogeochemical and Biogeophysical Impacts of Transient Land Cover Change and Wood Harvest in the Community Climate System Model (CCSM4) from 1850 to 2100. *Journal of Climate*, doi:10.1175/JCLI-D-11-00256.1.

Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G., et al., 2009: Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*: 1-6.

Matthews, J., A. Seimon, M. Mulligan, N. Sindorf, S. Burke and C. Shields (2011): An Assessment of the Climate Change Vulnerability of Rwanda's Wetlands: Integrating Eco-hydrological, Socio-economic, and Institutional Perspectives, Prepared for the Global Environment Facility by Conservation International.

McSweeney, R., 2011, Rwanda's climate: observations and projections. Smith School of Enterprise and the Environment, Oxford University, UK. Published online at: http://www.smithschool.ox.ac.uk/wp-content/uploads/2011/11/Climate-data-final_proofed.pdf

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor, 2007: The WCRP CMIP3 multi-model dataset: A new era in climate change research,*Bulletin of the American Meteorological Society,* **88**, 1383-1394.

Mitchell, T.D., Carter, T.R., Jones, P.D., Hulme, M., New, M., 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). Tyndall Centre for Climate Change Research Working Paper 55.

NAPA-Rwanda 2006. NAPA: The National Adaptation Programs of Action Reports. Available at: http://unfccc.int/cooperation_support/least_developed_countries_portal/submitted_napas/items/4585.php

NASA 2012: Tropical Rainfall Measuring Mission. Data available at http://pmm.nasa.gov/node/158

Nsabimana D., 2009. Carbon stock and fluxes in Nyungwe forest and Ruhande Arboretum in Rwanda. Doctoral thesis. Department of Plant and Environmental Sciences, University of Gothenburg, Sweden.

Perry, L.B., A. Seimon and G. M. Kelly (2013): Precipitation delivery in the tropical High Andes of southern Peru: New findings and paleoclimatic implications. *International Journal of Climatology*. In press.

Picton Phillipps, G. and A. Seimon, 2009: Potential Climate Change Impacts in Conservation Landscapes of the Albertine Rift, Wildlife Conservation Society whitepaper. Available at: http://www.albertinerift.org/DesktopModules/Bring2mind/DMX/Download.aspx?EntryId=11661&PortalId=49&DownloadMethod=attachment

Plumptre, A. J., T. R. B. Davenport, M. Behangana, R. Kityo, G. Eilu, P. Ssegawa, C. Ewango, et al. 2007: The Biodiversity of the Albertine Rift. *Biological Conservation*, 134:178–94

Raxworthy, C.J., Pearson, R.G., Rabibisoa, N., Rakotondrazafy, A.M., Ramanamanjato, J-B., et al., 2008: Extinction vulnerability of tropical montane endemism from warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar, *Global Change Biology*, **14**:1703-1720

Seimon, A. and A.J. Plumptre, (2012): The Albertine Rift. In M. Cross, J. Hilty and C. Chester (Eds.), Conservation and climate disruption: Landscape science and practice in a changing climate. Island Press

Seimon, A. and G. Picton Phillipps (2012): Regional Climatology of the Albertine Rift. In, A. Plumptre (Ed.), Long-term changes in Africa's Rift Valley, New York: Nova Science Publishers.

Seimon, A., J.C. Ingram and J.E.M. Watson (in press): Climatology of the East African Great Lakes Region and potential impacts of climate change on its biodiversity and ecosystem services. In, I. Gordon (ed.) Conservation Strategy in the Great Lakes Region of East and Central Africa, 2012. John D. and Catherine T. MacArthur Foundation, International Programs for Conservation and Sustainable Development.

Seimon and G. Picton Phillipps, 2009: Climatological Assessment of the Albertine Rift for Conservation Applications. Wildlife Conservation Society whitepaper. Available at: http://www.albertinerift.org/DesktopModules/Bring2mind/DMX/Download.aspx?EntryId=11659&PortalId=49&DownloadMethod=attachment

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

Smith School, 2011: Green Growth and Climate Resilience: National Strategy for Climate Change and Low Carbon Development for Rwanda Appendices, Smith School of Enterprise and the Environment, Oxford University, UK. Published online at: http://www.smithschool.ox.ac.uk/green-growth-and-climate-resilience-national-strategy-for-climate-change-and-low-carbon-development-appendices/

Storz, M. (1982). *La forêt naturelle de Nyungwe et sa faune.* Rapport Projet Pilote Forestier. Direction des Eaux et Forêts, Ministère de l'Agriculture et de l'Elevage, Coopération Technique Suisse.

Sun, C., Kaplin, B., Kristensen, K.A., Munyaligoga, V., Mvuklyumwami, J., Kajondo, K. & Moermond, T.C. (1996). Tree phenology in a tropical montane forest in Rwanda. *Biotropica, 28,* 668-681.

Thornton, P.K., P.G. Jones, G. Alagarswamy and J. Anresen, 2009: Spatial variation of crop yield response to climate change in East Africa. *Global Environmental Change*, 19: 54-65