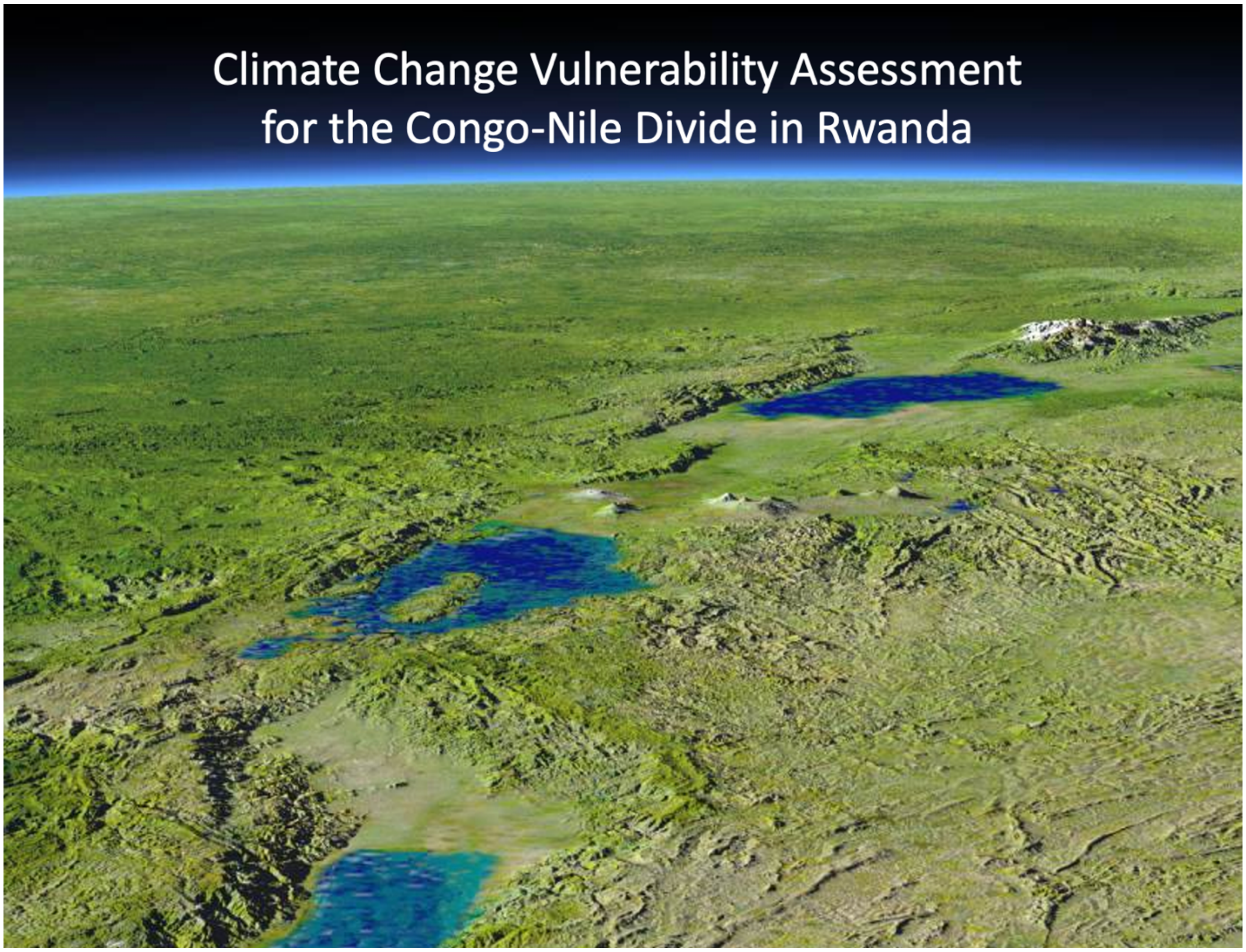
Annex 2.1



Prepared for the Wildlife Conservation Society Rwanda Country Program and Ministry of the Environment, Government of Rwanda

by

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Report organization

Section 1: Report overview

1a. Context of this document

This report provides the scientific basis for Section B.1, the Climate Context of the proposal entitled "Building Resilience of Vulnerable Communities to Climate Variability in Rwanda's Congo Nile Divide through Forest and Landscape Restoration". It combines findings from recent scientific literature emphasizing predictions from the suite of climate models utilized by the Intergovernmental Panel on Climate Change (IPCC), as well as climatological analysis and data, advanced environmental predictions and findings developed by the East African Great Lake Environment project (EAGLE) project [1]. Discussion on climate predictions is based primarily upon multi-model means of the suite of climate models comprising the Coupled Model Intercomparison Project's sixth phase (CMIP6: https://pcmdi.llnl.gov/CMIP6/), the basis for much of the Sixth IPCC Assessment Report. Results are shown for a range of paired Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathway (RCP) emission scenarios; for some variables emphasis is placed on a "pessimistic" high SSP-high RCP scenario (SSP5-8.5), since this exhibits greater distinction between present day and future conditions as a consequence of anthropogenic climate change. Specialized modeling performed at ultra-high (i.e., convection-allowing) resolution[2] for the EAGLE project, and findings from scientific literature are extensively utilized as well.

1b. A selection of take-home messages of this report

Temperature increase is already ongoing and likely irreversible throughout the CND region for several decades to come. However, local impacts can be ameliorated considerably, to the benefit of biodiversity and ecosystem services, by restoring forest cover and augmenting moisture retention in the landscape, which both serve to promote increased cloud cover and generate localized cooling.

Warming is causing uphill displacements of a wide range of organisms and ecological processes -- and possibly even entire montane ecosystems -- with the rate of ascent directly proportional to the magnitude of warming trends. **With approximately +2.6°C of warming over 20th century baseline conditions** almost certain to occur by mid-century, **this translates to a vertical increase on the order of 473 meters from thermal conditions experienced in the recent past** prior to anthropogenic climate warming.

Precipitation seasonality may change, upending annual climatological patterns with potential to disrupt biodiversity, environmental systems and agricultural practices in fundamental ways. This possibility is raised by novel simulations of rainfall along the CND performed for the EAGLE project at ultra-high resolution, which show the total disappearance of the mid-year dry season by the period 2055-64, and sustained thereafter. This requires further investigation and examination of current trends, but the possibility that this may come to pass behooves serious consideration by environmental planners.

Precipitation intensity change, whereby a warming climate will have the consequence of increasing short-period rainfall rates and individual storm totals, especially for the fraction of higher-end events that can cause flash flooding and promote landslides. **This is certain to**

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[1] https://www.eagleclimate.org

[2] Grim, J. A., Pinto, J. A., Jensen, A. A., & Seimon, A., 2020: The East African Great Lake Environments (EAGLE) Climate Downscaling Dataset. Link

occur, is probably already discernible, and likely to amplify very significantly over time as warming progresses.

Cloud base altitude, which is highly influential in montane forest ecology and species composition, **is likely already elevated above recent past conditions due to conversion of forests to agricultural lands, and certain to rise further in proportion to the degree of warming over coming decades.** Ecosystems and species assemblages in the lower reaches of protected forests may already be out of balance with this important environmental variable, and this imbalance will only increase over time, promoting rapid species turnovers, enhance potential for invasives, and act as a strong driver of upward range extensions.

Fog interception by vegetation also augments montane forest precipitation by an estimated 10%, so rising cloud bases will act to remove this important hydrological input too. **Highland forest loss therefore represents a local loss to the ecosystem service of rainwater provision (by about 10%) that could be partially restored through reforestation.**

It is unclear if wildfire risk is or is not increasingly significantly, but can likely be managed though enhanced vigilance during drought events.

Section 2: Temperature trends and predictions

2a. Topography of the Congo-Nile Divide in climatic contexts

The climate of western Rwanda and its CND landscape features conditions highly supportive of tropical montane forests, rich biodiversity and human activities alike. Despite being located deep in the tropics just south of the equator, the elevated terrain of the CND corridor, mostly above 2,000 meters, ensures relatively cool temperatures through the year (**Figure 1**).

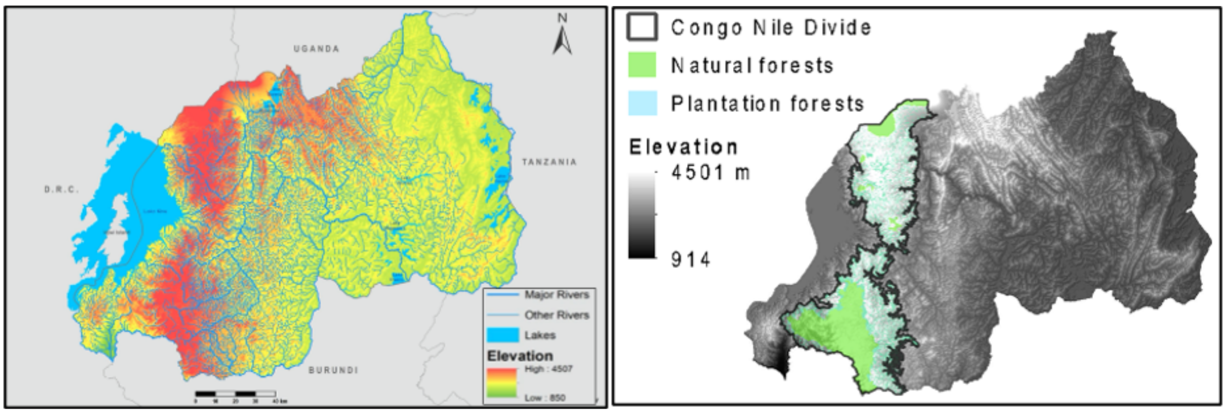

Figure 1. (**left**) Topographic map of Rwanda with riverine drainage channels overlaid. Source: Rwanda Atlas (2019)[3]; (**right)** Congo Nile Divide, identified by the 1,900 m elevation contour and showing the presence of natural and plantation forests. Source: CND project team.

Prior to landscape conversion for agricultural purposes, continuous dense forest cover yielded augmentation of precipitation through fog interception in tree canopies, and near-daily cloud immersion sustained cloud forest ecosystems and species assemblages. The forests also maintained slope stability in steep terrain and yielded percolation and groundwater recharge rather than direct runoff of heavy precipitation. Such conditions are now constrained to within the CND's protected forests within national parks, covering just 30% of the CND landscape and just 5% or Rwanda's total land surface. These are Rwanda's only remaining montane forests, yet represent 58.7% of national carbon stocks[4] and are imperiled by intense population pressures, with approximately 32.4% of the country's population residing within the CND landscape.

2b. Observed temperature trends

A reconstruction of temperatures for the past 140 years for Rwanda, based on quality controlled instrumental records and centered on Kigali, shows that global climate change already has strong local expression. Rapid temperature increase commenced in the 1970s, with a net gain of approximately +1.1°C since 1970[5] (**Figure 2**). This compares to the global mean from the same authoritative data set of +1.3°C, showing the thermal increase in Rwanda is consistent with warming as experienced globally.

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[3] Vital Signs, 2019: Rwanda Atlas. Environment, Agriculture and Livelihood Options. Vital Signs and WCS Rwanda. Link.

[4] Mugabowindekwe, Maurice and 21 coauthors: Nation-wide mapping of tree level carbon stocks in Rwanda. Manuscript in review (Oct 2022). Link.

[5] Berkeley Earth Rwanda Country Profile at www.berkeleyearth.org

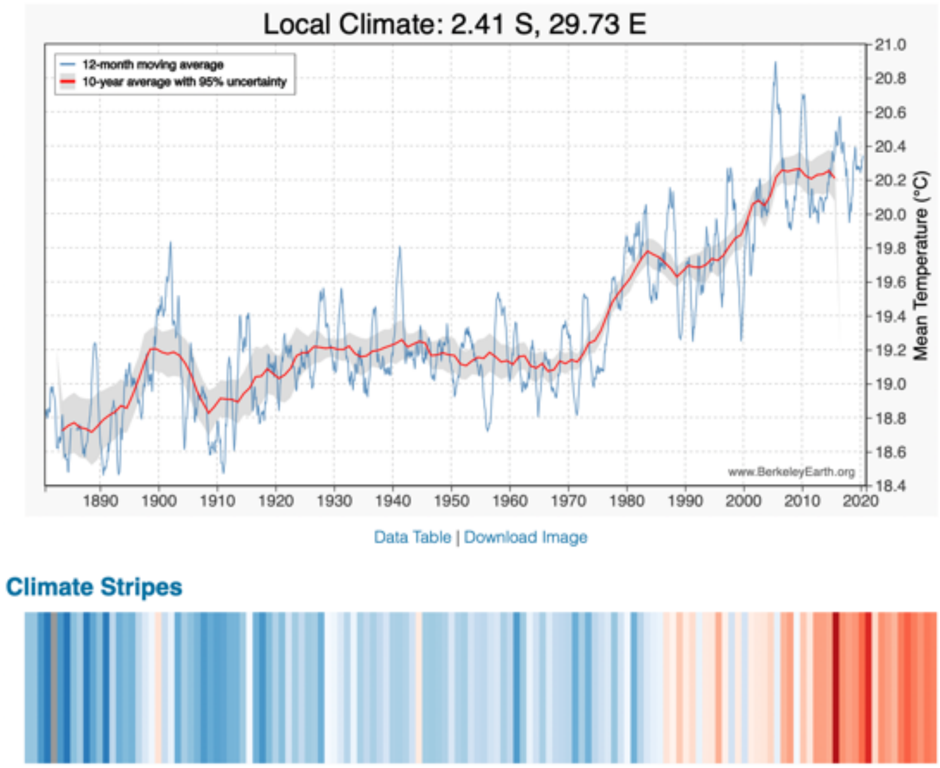

Figure 2. Berkeley Earth temperature reconstruction based on instrumental measurements for Kigali in central Rwanda. The "Climate Stripes" offers a visual display that effectively communicates both individual year temperature anomalies and the overall multi-decadal trend behavior. Source: Berkeley Earth Rwanda Country Profile.

The regional warming of the climate over the past half-century coincided with widespread forest conversion to farmland along the CND. As a consequence, at fine spatial scales climatic conditions across the CND at present mimic the landscape mosaic, whereby only the protected forests will retain much of the past climatic character while converted landscapes are likely to be significantly warmer by day, have reduced cloud cover and higher cloud bases, and experience slightly reduced rainfall as well.

2c. Temperature predictions to mid and late century

As with almost all locations on Earth, annual average temperature across the CND will continue to rise inexorably over coming decades; due to the current buildup of greenhouse gases this holds true regardless of what actions the global community and Rwandan national government take. Localized projections for the CND landscape of climatic changes present a strong consensus on temperature increase for the next two decades. The magnitude of net temperature change by late-century, and the tendency of warming to accelerate, hold steady, decelerate or even begin an overall temperature decline is unknowable at present, but a large number of climate model simulations show common patterns, whereby divergence in possible temperature outcomes will only become apparent around 2040[6] (**Figure 3**).

[6] World Bank Climate Change Knowledge Portal. Link

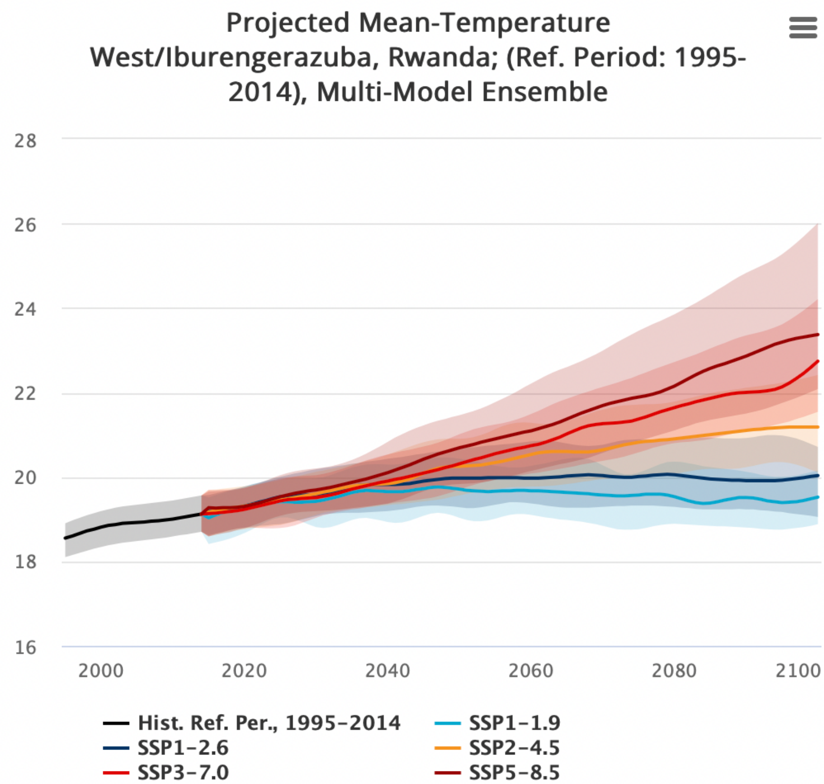

Figure 3. CMIP6 multi-model ensemble predictions for mean annual temperature over western Rwanda across the 21st century under a variety of SSP-RCP combinations. Source: World Bank

These results are also consistent with outputs from the previous CMIP5 model suite for western Rwanda (e.g., IFAD report 2020)[7]. As such, using the consensus values of such models is a sensible choice for environmental planning, with a +2.0 °C increase over the IPCC-referenced 1995-2014 baseline conditions offering a representative value for warming by mid-century. However, the observed warming of +0.6 °C registered between 1970-95 prior to the IPCC baseline period must be recognized as well, suggesting **net warming of +2.6 °C from a more representative 20th century baseline**.

In common with moist environments within the inner tropics, temperature variations across the course of the year along the CND are very small. This uniformity means that forthcoming temperature increases are unlikely to be noticeably more or less intense at any particular time of the year. Grid point output for the Nyungwe Forest region from a global CESM model simulation of past monthly mean temperature and projections to century's end under the RCP 8.5 high emissions pathway suggest that an accelerating upward trend in temperature will progress with relative uniformity throughout the year[8] (**Figure 4**). It is noteworthy that by 2060, the coolest month of the year, July, would have mean temperatures higher than the warmest month of the year, October, in 2000.

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[7] Hunter. R., Crespo. O., Coldrey, K, Cronin, K, New, M. 2020. Research Highlights – Climate Change and Future Crop Suitability in Rwanda. International Fund for Agricultural Development (IFAD), Rome.

[8] Seimon, A., 2012: Climatology and Potential Climate Change Impacts of the Nyungwe Forest National Park, Rwanda. WCS White paper report, Wildlife Conservation Society, New York, USA, 44 pp.

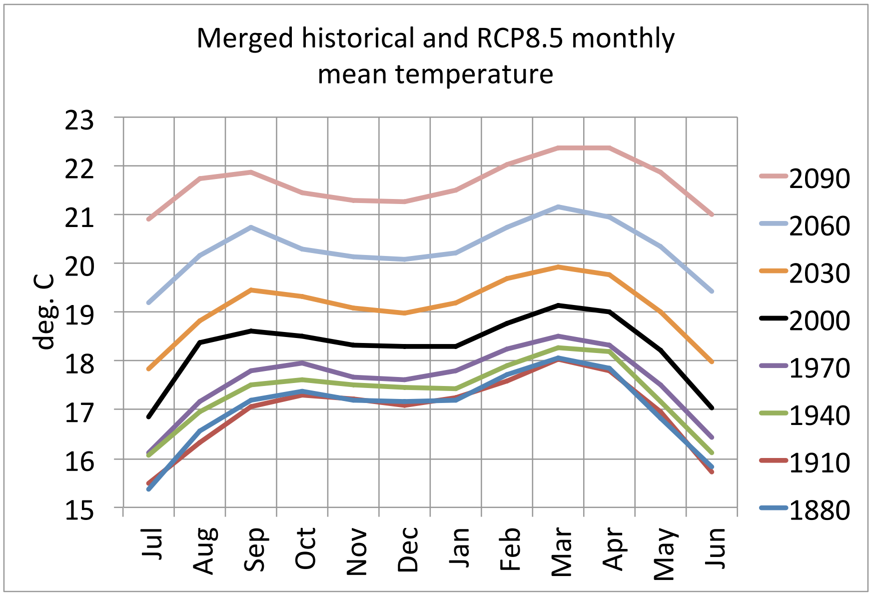

Figure 4. Monthly mean temperatures at 30-yr intervals spanning 1880-2090 for a 1x1 degree lat-lon grid cell covering the southern CND in Rwanda including Nyungwe Forest, from joint historic and future simulations of the Community Earth System Model (CESM) under the high emissions RCP 8.5 scenario. Source: Nyungwe climate assessment report (Seimon 2012)

The magnitude of temperature change shows little variation across space when displayed at relatively coarse global model resolutions across broad regions. This can be seen in standard projections from the IPCC model suite, such as shown below[9] (**Figure 5**).

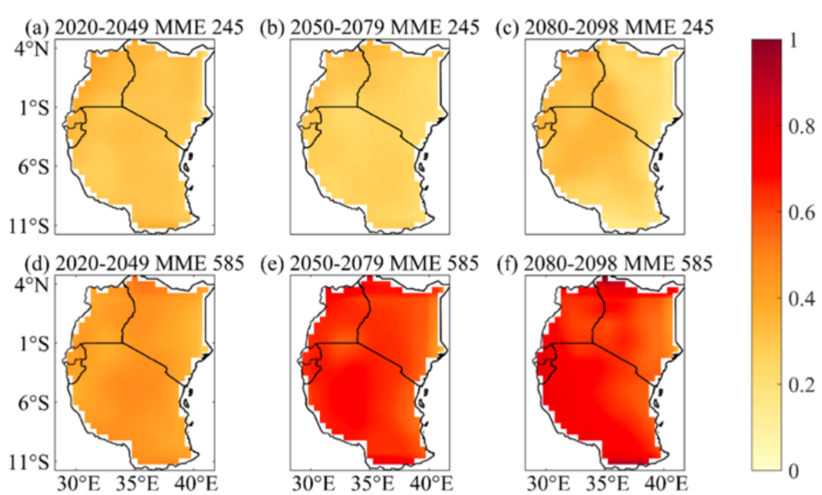

Figure 5. Spatial distribution of annual mean temperature trends (°C per decade) over EA land surface in near-term (2020 – 2049), mid-term (2050 – 2079), and long-term (2080 – 2100) periods of the 21st century under the SSP2 – 4.5 and SSP5 – 8.5 scenarios. Source: Ayugi et al., 2021

[9] Ayugi, B., Ngoma, H., Babaousmail, H., Karim, R., Iyakaremye, V., Sian, K.T.L.K. and Ongoma, V., 2021. Evaluation and projection of mean surface temperature using CMIP6 models over East Africa. *Journal of African Earth Sciences*, *181*, p.104226.

Simulations of future temperatures conducted at fine scales, however, suggest a considerable amount of spatial variation in the magnitude of warming may become apparent over time, whereby geographic factors such as proximity to large water bodies and extant forests would serve to damper warming signals. Such a signal is evident by late century in the CND region in the EAGLE project's 3.3 km resolution simulation[10], with the Lake Kivu basin exhibiting reduced warming relative to the CND (**Figure 6**). At the time scales of the current GCF project, such variations are likely to be relatively inconsequential. However, it should be recognized that extensive highland reforestation holds the potential to significantly reduce the magnitude of warming in those areas. This could be explicitly quantified by running the same model with increasing forest fractions prescribed accordingly.

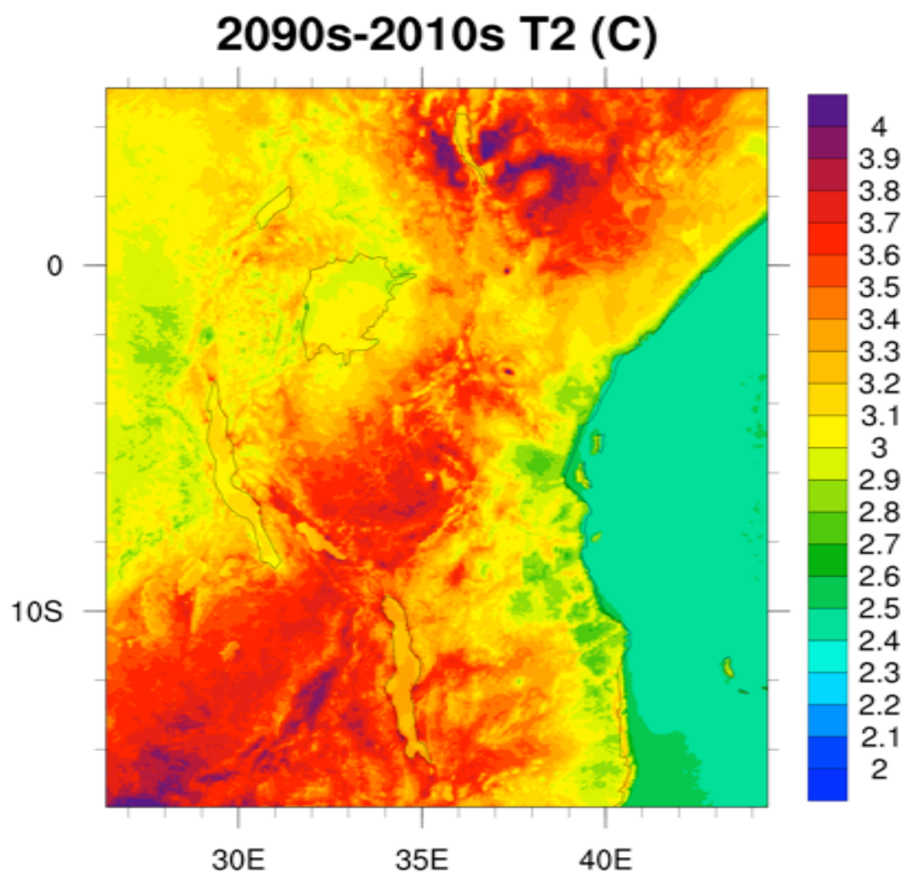

Figure 6. Ultra-high resolution model simulation of annual mean near-surface (2 meter) temperature difference comparing the end of century decadal period 2090-99 with a decade of the recent past (2009-18). This simulation, performed using the Weather Research and Forecasting (WRF) model utilized boundary conditions provided by a global simulation of the Community Earth System Model (CESM) under the high emission RCP 8.5 scenario. Source: EAGLE project and Grim et al., 2020.

[10] Grim, J. A., Pinto, J. A., Jensen, A. A., & Seimon, A. (2020). The East African Great Lake Environments (EAGLE) Climate Downscaling Dataset (NCAR Technical Note TN-563+STR).

Section 3: Hydroclimatology trends and predictions

There are several fundamental ways that moisture dynamics of the CND are prone to modification by climate change of patterns experienced to the present that have shaped biodiversity distributions, species phenologies, agricultural practice and a host of human activities. These include:

- Precipitation amount, whereby annual accumulations may trend upward, downward or remain on par with present day values;

- Precipitation seasonality, whereby the distribution of rainfall over the annual cycle may change over time;

- Precipitation intensity, whereby a warming climate will have the consequence of increasing short-period rainfall rates and individual storm totals, especially for the fraction of higher-end events that can cause flash flooding and promote landslides;

- Landscape desiccation, whereby increasing temperatures will significantly increase the rate that water can be extracted from vegetation and soils during dry periods.

- Cloud base altitude, which is highly influential in montane forest ecology

Each is examined and evaluated in the context of climate model predictions sequentially below.

3a. Annual mean precipitation changes.

Due to the fortuitous combination of high elevation and ridgeline orientation that intercepts prevailing airflows, the CND in Rwanda is characterized by abundant rainfall for much of the year, and represents the primary “water tower” of the nation. The Nyungwe Forest in particular is the wettest region of Rwanda, and is of major importance in sustaining river flows downstream during the mid-year dry period, whereby the protected forest is instrumental in ensuring water release even in the absence of rainfall[11]. Rainfall is abundant for nine out of 12 months, and a reliable mid-year dry season adds dynamic character to phenological cycles, pollinator activity and agricultural practices (**Figure 7**). Such characteristics highlight the susceptibility of the CND landscape to hydrological perturbation associated with climatic change, so need to be considered carefully.

[11] Seimon, A., 2012: Climatology and Potential Climate Change Impacts of the Nyungwe Forest National Park, Rwanda. WCS White paper report, Wildlife Conservation Society, New York, USA, 44 pp.

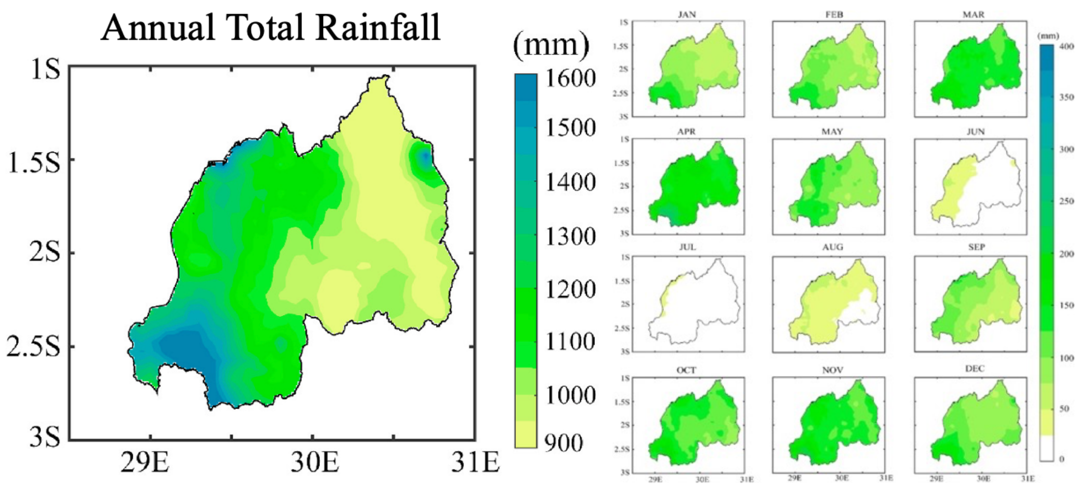

Figure 7. Annual (**left**) and monthly (**right**) rainfall (mm) climatology over Rwanda (period of record: 1981–2017), based on algorithms that calibrate satellite-based rainfall estimates with surface observations. Source: Jonah et al., 2021[12]

The CMIP6 results for precipitation changes over coming decades are less consistent than the temperature projections. Recent studies focused in East Africa have identified limitations to global model utilization for regionally specific predictions, such as failure to represent observed precipitation magnitude and distribution in the present, and reliance on approximations (i.e., parameterizations) that inadequately represent the role of convective storms in precipitation delivery[13]. The CMIP6 ensemble means for annual precipitation over western Rwanda have a baseline value of approximately 2,000 mm per year, which is considerably higher than actual values (**Figure 8**). The higher emissions scenarios show increasing totals over time, which is plausible given the increasing water vapor carrying capacity of a warming atmosphere. Strangely, the most optimistic scenario (SSP1-1.9) shows strongly varying trends at decadal scales, increasing far more rapidly in the near-term than other scenarios. Such inconsistencies reduce confidence in the overall product suite for precipitation predictions.

There is also major inconsistency between CMIP model suites. As assessment for western Rwanda from CMIP5 under RCP 8.5 comparing historical and mid-century outputs suggested rainfall decreases of 5-10% in most months, with net annual decrease of 86 mm[14]; the baseline time periods and geographic domains of these two CMIP ensemble compilations for western Rwanda differ, but the reversal from drier to wetter gives low confidence in the utilization of precipitation predictions specific to the CND if derived from global models.

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[12] Jonah, K., Wen, W., Shahid, S., Ali, M.A., Bilal, M., Habtemicheal, B.A., Iyakaremye, V., Qiu, Z., Almazroui, M., Wang, Y. and Joseph, S.N., 2021. Spatiotemporal variability of rainfall trends and influencing factors in Rwanda. *Journal of Atmospheric and Solar-Terrestrial Physics*, *219*, p.105631.

[13] Wainwright, C.M., Marsham, J.H., Rowell, D.P., Finney, D.L. and Black, E., 2021. Future changes in seasonality in East Africa from regional simulations with explicit and parameterized convection. *Journal of Climate*, *34*(4), pp.1367-1385.

[14] Hunter. R., Crespo. O., Coldrey, K, Cronin, K, New, M. 2020. Research Highlights – Climate Change and Future Crop Suitability in Rwanda. University of Cape Town, South Africa. International Fund for Agricultural Development (IFAD), Rome.

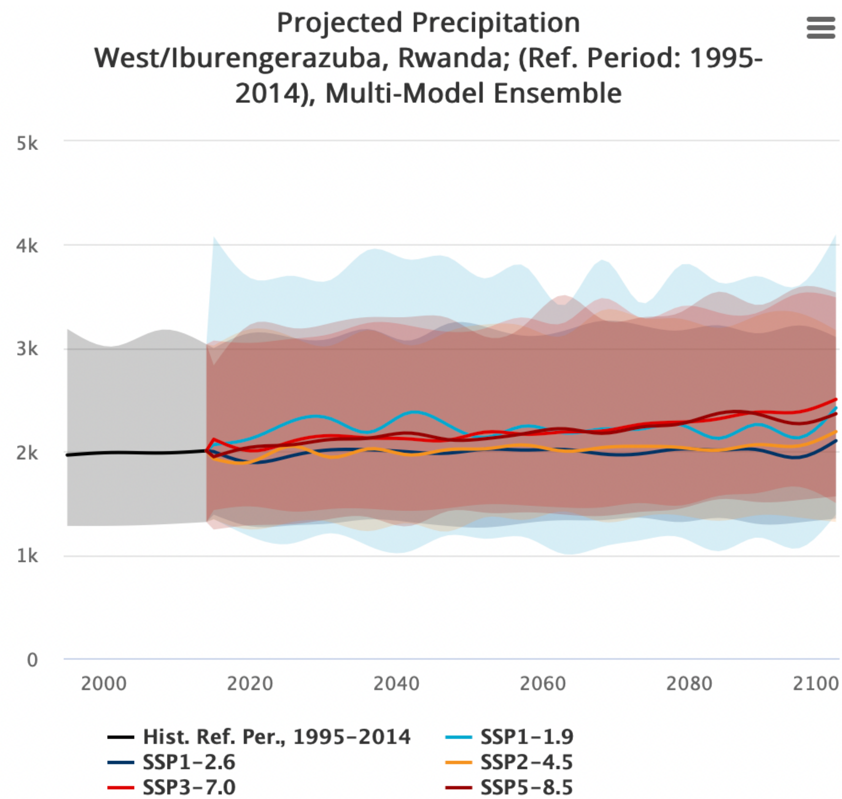

Figure 8. CMIP6 multi-model ensemble prediction for mean annual precipitation over western Rwanda across the 21st century under a variety of SSP-RCP combinations. Left-axis scale is thousands of mm per year. Source: World Bank[15]

To generate more refined results, the EAGLE project performed regional simulations of East African climate at ultra-fine, convection-allowing scale (WRF model at 3.3 km model resolution); these were based off the global CESM2 model (part of the CMIP6 suite) boundary conditions under the high emissions RCP8.5[16]. The regional model was configured to optimize parity with regional climate station data. The resulting high spatial resolution output suggests a strongly amplified rainfall signal over the 21st century over western Rwanda relative to the CMIP6 ensemble mean for RCP 8.5 (**Figure 9**). Also notable is that the rest of Rwanda exhibits far smaller increases, suggesting that the CND's hydrological significance as water tower for the nation would be reinforced over time.

[15] World Bank Climate Change Knowledge Portal. Link

[16] Grim, J. A., Pinto, J. A., Jensen, A. A., & Seimon, A. (2020). The East African Great Lake Environments (EAGLE) Climate Downscaling Dataset (NCAR Technical Note TN-563+STR).

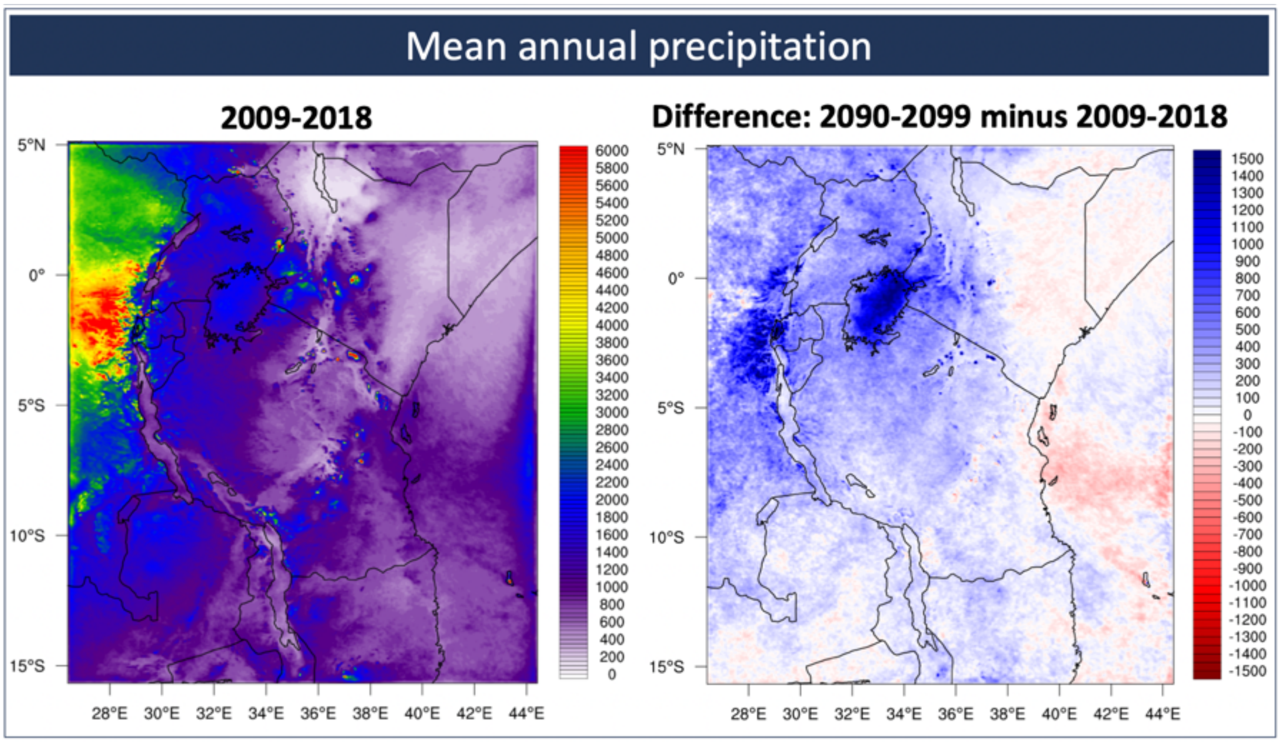

Figure 9. EAGLE project high-resolution WRF simulation of annual mean precipitation (mm/yr) (**left**) and difference between end of century and recent past (**right**) across East Africa. The CND landscape and Like Kivu show comparable increases to Lake Victoria, and represent the largest rainfall increases across the modeled domain. Source: EAGLE project and Grim et al. (2020)[17]

The EAGLE project outputs offer some additional insights. In a study on CESM predictions for the Lake Kivu-Rusizi River watershed that forms the west side of the CND landscape, wet season precipitation showed marked increases and a shift to an earlier pluvial peak over the course of the century[18] (**Figure 10**). The subsequent high-resolution WRF modeling described above shows the CND highlands and Lake Kivu within a regional maximum in precipitation increase by the end of the century, amounting to 1,000 mm or more above those modeled for the 2009-18 period, which were calibrated through bias correction against actual observations[19] (refer to Figure 9**).**

[17] Grim, J. A., Pinto, J. A., Jensen, A. A., & Seimon, A. (2020). The East African Great Lake Environments (EAGLE) Climate Downscaling Dataset (NCAR Technical Note TN-563+STR).

[18] Seimon, A., P. Lawrence and S. Nampindo, (2016): High-Resolution Climate and Environment Predictions. Chapter 7 in I. Gordon and A. Schenk (eds.), CRAG Implementation Plan for the Lake Kivu-Rusizi Region. BirdLife International.

[19] Grim, J. A., Pinto, J. A., Jensen, A. A., & Seimon, A. (2020). The East African Great Lake Environments (EAGLE) Climate Downscaling Dataset (NCAR Technical Note TN-563+STR).

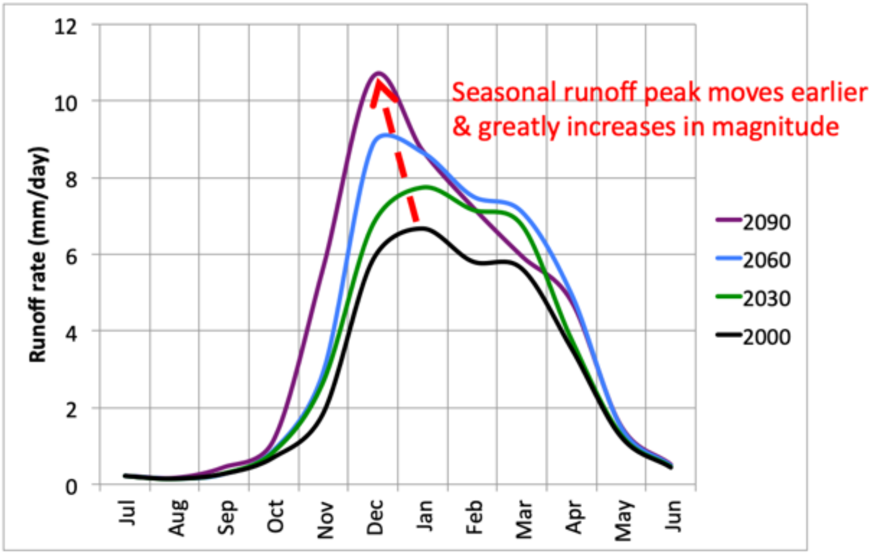

Figure 10. Mean monthly rainfall for the Lake Kivu-Rusizi River region forming the west side of the CND landscape at four time points across the 21st century. Source: Seimon et al., 2016

3b. Precipitation seasonality

The annual cycle of climate along the CND sees abundant rainfall for much of the year interrupted by a marked dry season in the June-August months when rainfall becomes light and sporadic, and during which hydrological deficits develop as evaporation far exceeds precipitation and resultant runoff. While highland orography largely explains the enhanced rainfall along the CND, the occurrence of the dry seasons occurs regionwide irrespective of terrain elevation (**Figure 11**, see also Figure 2b above).

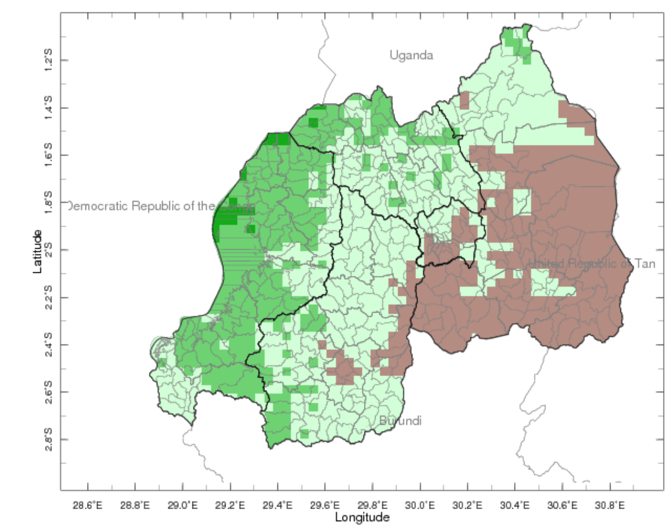

Figure 11. The average number of days with rainfall exceeding 3 mm for the months of June-August. The wettest parts of the CND only receive significant rainfall on ~10% of days during the dry season peak. Source: ENACTS online tool at Meteo Rwanda[20]

[20] ENACTS online tool at Meteo Rwanda: http://maproom.meteorwanda.gov.rw

This finds explanation in the seasonal north-south migration of a pan-equatorial band of enhanced cloudiness, the Inter Tropical Convergence Zone (ITCZ)[21]. The slight reduction in rainfall experienced over several weeks along the CND in January and February reflects much more pronounced dryness to the north in Uganda; conversely, the more defined mid-year dry season along the CND spanning June through August is associated with enhanced southeasterly airflows that effectively push the zone of atmospheric convergence promoting rainfall across the equator into Uganda (**Figure 12**)

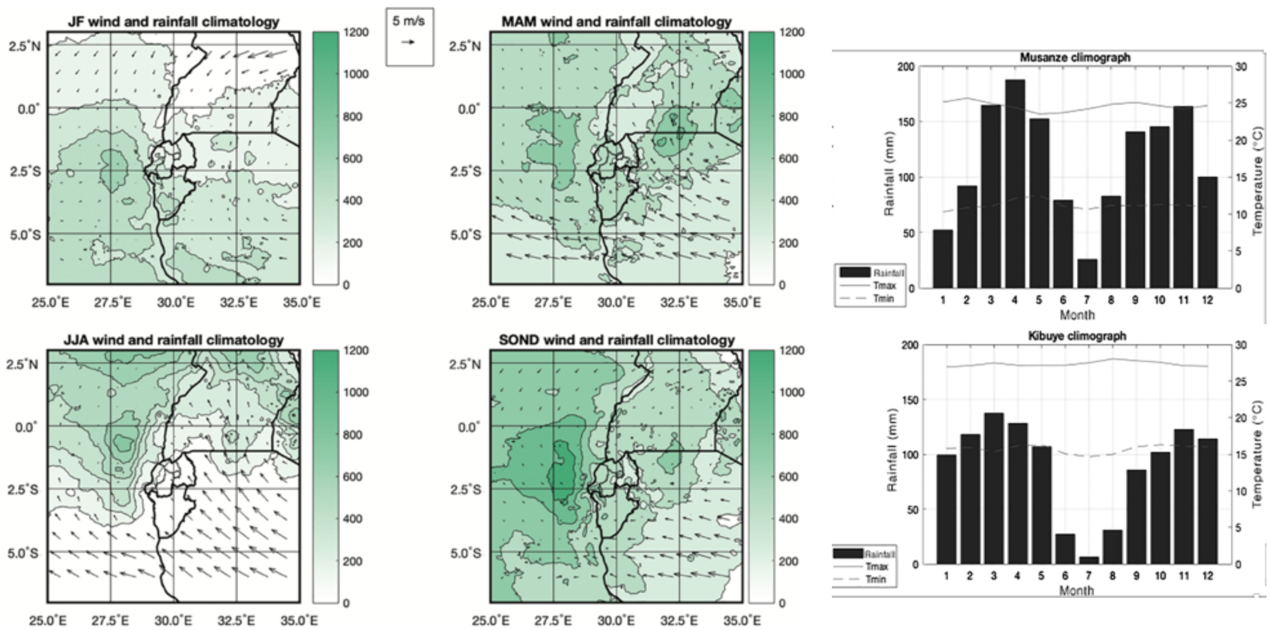

Figure 12. (**left panel)** (Original figure caption) Seasonal precipitation and 850 hPa wind climatologies in the vicinity of Rwanda from CHIRPS (Funk et al., 2015)[22] and ERA-Interim reanalysis (Dee et al., 2011)[23], respectively, for 1987–2016. Rainfall units are in mm. (a) January–February, (b) March–May, (c) June–August and (d) September– December. Isohyet contours are placed every 100 mm for (a, c) and every 200 mm for (b, d). A scaled wind vector is also displayed. (**right panel**) Climographs indicating mean rainfall (columns) and temperature (lines) for Musanze (29.63E, 1.5S, 1,850 m) and Kibuye (29.35E, 2.06S, 1,514 m). Source for both figures: Siebert et al., 2019[24]

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[21] Siebert, A., Dinku, T., Vuguziga, F., Twahirwa, A., Kagabo, D.M., delCorral, J. and Robertson, A.W., 2019. Evaluation of ENACTS-Rwanda: A new multi-decade, high-resolution rainfall and temperature data set—Climatology. *International Journal of Climatology*, *39*(6), pp.3104-3120.

[22] Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell A., and Michaelsen, J. (2015) The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Scientific Data, 2.

[23] Dee, D.P and coauthors, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137, 553–597.

[24] Siebert, A., Dinku, T., Vuguziga, F., Twahirwa, A., Kagabo, D.M., delCorral, J. and Robertson, A.W., 2019. Evaluation of ENACTS-Rwanda: A new multi-decade, high-resolution rainfall and temperature data set—Climatology. *International Journal of Climatology*, *39*(6), pp.3104-3120.

In this light, an unusual finding from the EAGLE project's high-resolution modeling studies is that the CND landscape has a heightened risk of major change in climatic seasonality. By the 2055-64 period: the mid-year dry season effectively disappears (**Figure 13**). Being the output of a single model run under a high-end greenhouse gas emissions scenario may make this seem implausible; it is highly dissimilar from mid-century predictions of the consensus of global models, which sustain the dry season. It finds corroboration, however, in a new study on East African rainfall which found that the parameterization of convection in global models may be a source of uncertainty for projections of changes in seasonal timing, and that potentially impactful changes in seasonality are therefore quite plausible[25]. Such an eventuality is exceptionally difficult to plan for, and since it would only come to fruition well after the project period, if at all, additional studies could be conducted to provide needed guidance.

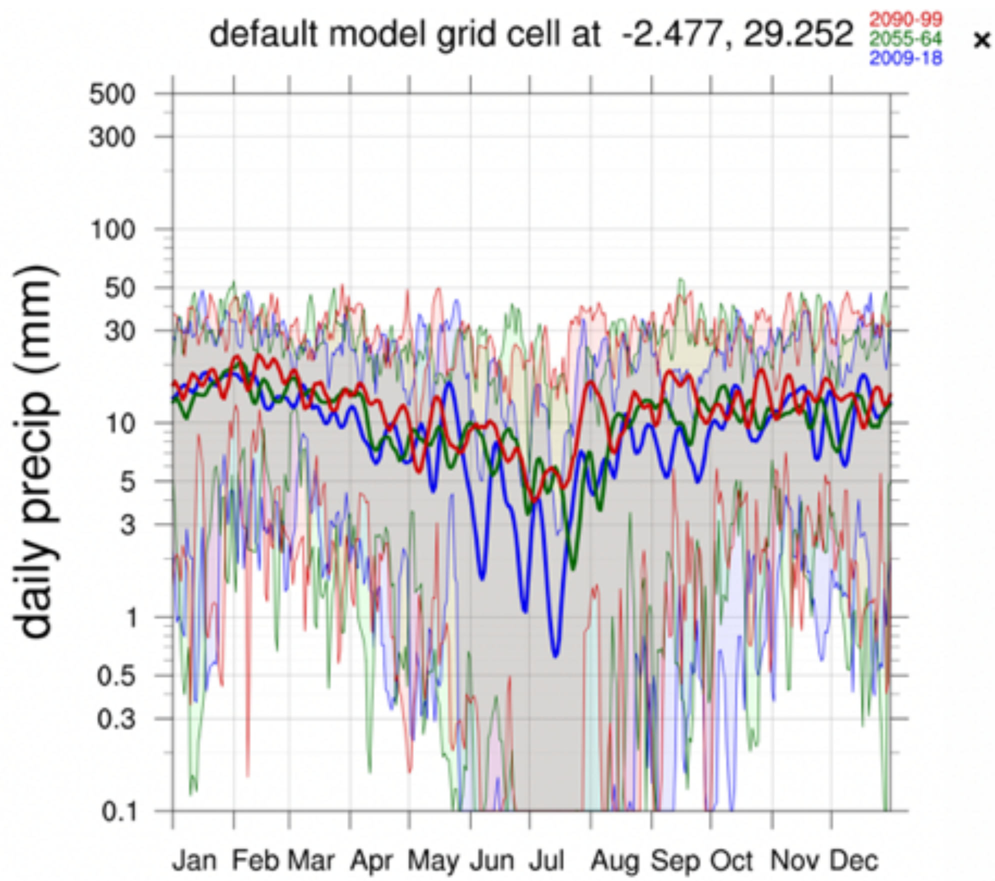

Figure 13. Annual cycle of rainfall rate (mm/day, note logarithmic scale) at Nyungwe Forest National Park showing daily means (thick lines) and extremes (thin lines) for 10-year time periods centered on 2014 (blue), 2060 (green) and 2095 (red). The dry season evident in the 2014 mean reaching below 1 mm/day, effectively disappears by the 2060 time period. <u>Source</u>: EAGLE project[26]

[25] Wainwright, C.M., Marsham, J.H., Rowell, D.P., Finney, D.L. and Black, E., 2021. Future changes in seasonality in East Africa from regional simulations with explicit and parameterized convection. *Journal of Climate*, *34*(4), pp.1367-1385.
[26] EAGLE project website: https://www.eagleclimate.org/climate/#

3c Precipitation Intensity

Due to the increased moisture carrying capacity of warmer air (7% increase per degree of warming)[27], ongoing climatic warming promotes increasingly intense short-period rainfall, which acts synergistically with landscape conversion on steep slopes to cause quickflow runoff, yielding large increases in landslide occurrence and soil erosion more generally (**Figure 14**). With its high topographic relief, the CND is highly susceptible to soil erosion. Throughout Rwanda, soil erosion has increased by 54% since 1990 with the bulk of the increase experienced and highest erosion levels over western Rwanda[28]. Between January and June in 2018, landslides caused more than 200 mortalities[29], and in May 2020, 65 deaths from landslides and flash flooding occurred during a single night of storms focused on the eastern slopes of the CND[30].

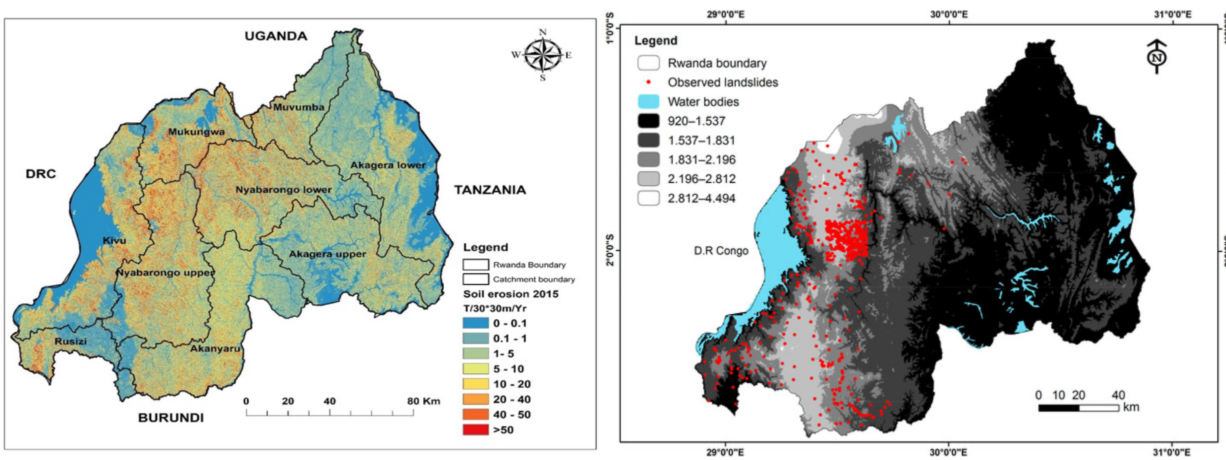

Figure 14. (**left**) Intensity of soil erosion in Rwanda assessed for the year 2015. Source: NISR 2019. (**right**) Observed landslide occurrences in Rwanda against a topographic background, showing intense clusters along both the east and west sides of the CND landscape. Source: Nsengiyumva et al., 2018[31]

Due to well-understood physical properties of the atmosphere, as warming progresses short-period rainfall rates and individual storm totals, especially for the fraction of higher-end events that can cause flash flooding and promote landslides, will increase and should amplify very significantly over time[32]. The CMIP6 ensemble means for monthly counts of days with heavy precipitation suggest an upward trend is now underway (**Figure 15**). Forthcoming increases are most pronounced for November through January. Such increases in heavy precipitation events

[27] Trenberth, K.E., 2011. Changes in precipitation with climate change. Climate research, 47(1-2), pp.123-138.
[28] NISR: National Institute of Statistics of Rwanda, 2019
[29] Reuters 2018. https://www.reuters.com/article/us-rwanda-floods-idUSKBN1I81I
[30] Associated Press 2020. https://apnews.com/article/b7658b76a403fd9bc8cba249f9d484fd
[31] Nsengiyumva, J.B., Luo, G., Nahayo, L., Huang, X. and Cai, P., 2018. Landslide susceptibility assessment using spatial multi-criteria evaluation model in Rwanda. *International journal of environmental research and public health*, *15*(2), p.243.
[32] Fowler, H.J., Ali, H., Allan, R.P., Ban, N., Barbero, R., Berg, P., Blenkinsop, S., Cabi, N.S., Chan, S., Dale, M. and Dunn, R.J., 2021. Towards advancing scientific knowledge of climate change impacts on short-duration rainfall extremes. *Philosophical Transactions of the Royal Society A*, 379(2195)

are to be expected under a warming climate and are of major social and ecological concern, being a driver of landslide occurrences and major contributors to soil erosion intensity.

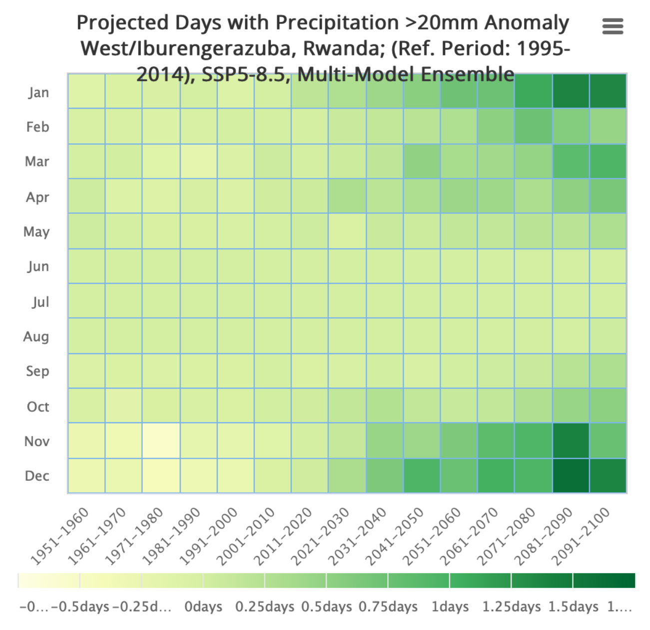

Figure 15. CMIP6 multi-model ensemble prediction for monthly changes in the number of days with rainfall >20 mm over western Rwanda across the 21st century under RCP8.5. Source: World Bank[33]

Another major concern for the future is the hydroclimatology of the CND landscape. A very important principle here is that temperature increase yields an outsized response when it comes to moisture in the atmosphere (the Clausius-Clapeyron relation: see e.g., Trenberth 2011[34]). For each degree centigrade that temperature increases (so, a linear change), the moisture carrying capacity of air increases by about 7% (an exponential change). This has consequences for both wet and dry conditions. As temperatures increase, rainfall intensity, especially for extreme events, will increase according to this exponential relationship. There is recent observational evidence and modeling, however, which show that this relationship may be higher than the 7% per degree ratio in intense short-period precipitation events[35].

The steep hillsides that characterize much of western Rwanda will therefore experience intensifying erosion and risk of landslides, while built infrastructure such as road and bridges will be overwhelmed since they were engineered to withstand rainfall intensities expected under past climatic conditions that are sure to be exceeded, and with increasing frequency, as time progresses and temperatures steadily increase.

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[33] World Bank Climate Change Knowledge Portal. Link

[34] Trenberth, K.E., 2011. Changes in precipitation with climate change. *Climate Research*, 47, pp.123-138.

[35] Fowler, H.J., Ali, H., Allan, R.P., Ban, N., Barbero, R., Berg, P., Blenkinsop, S., Cabi, N.S., Chan, S., Dale, M. and Dunn, R.J., 2021. Towards advancing scientific knowledge of climate change impacts on short-duration rainfall extremes. *Philosophical Transactions of the Royal Society A*, 379(2195)

3d. Landscape Desiccation and Vapor Pressure Deficit trends

Drought/dry spells. Warming will also increase the propensity for vegetation to desiccate during dry spells, intensifying wilting of natural vegetation and cultivars. The capacity of air to extract moisture from landscapes through direct evaporation and evapotranspiration of vegetation will also increase exponentially as temperatures rise. This means that land surfaces and vegetation will dry out more quickly between rainfall episodes in the future than in the past. It also means that to maintain hydrological balances that natural and human systems depend upon, total rainfall must increase in proportion to intensifying evaporation rates. The CMIP6 ensemble results for the CND region suggest such a favorable balance may indeed be maintained through at least mid-century (**Figure 16**). Under the full range of emissions scenarios considered, there is almost no change in ensemble means through mid-century.

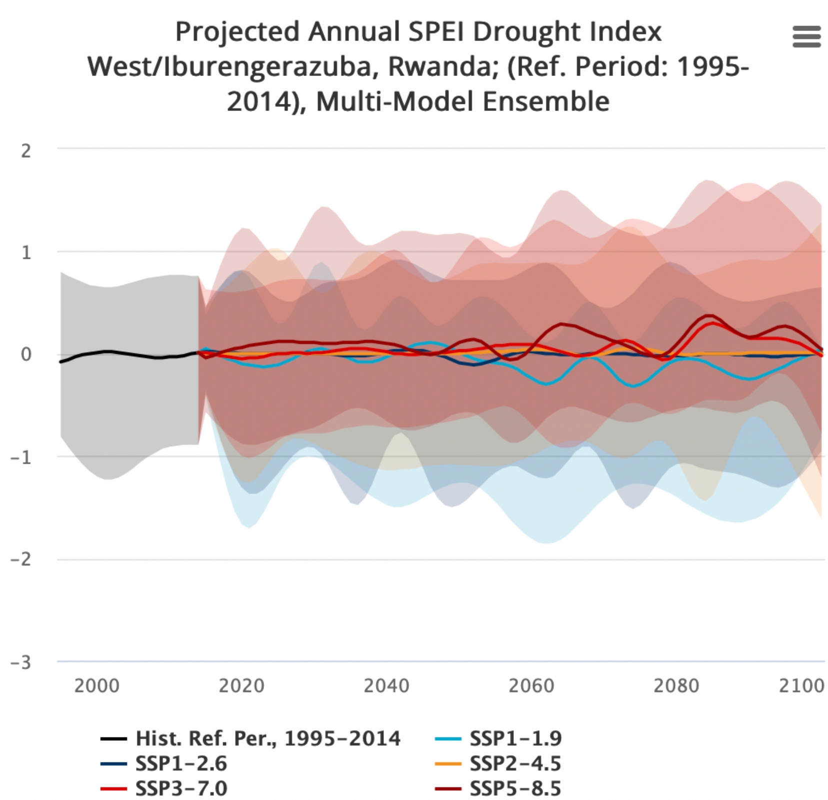

Figure 16. Western Rwanda CMIP6 model-model ensemble mean time series of the Standardized Precipitation Evapotranspiration index (SPEI) for a range of climate change scenarios across the 21st century. The SPEI is a measure of the integrated water deficit in a location, taking into account the contribution of temperature dependent evapotranspiration of a 12-month period. Source: World Bank[36]

A more useful variable for assessing drought potential at daily-seasonal times scales is the Vapor Pressure Deficit (VPD). This is an absolute measure of the difference between the water vapor content of the air and its saturation value, and as such, represents a direct metric of the ability of

[36] World Bank Climate Change Knowledge Portal. Link

the atmosphere to extract moisture from the land surface[37]. High resolution VPD predictions for present day, mid-century and late-century under boundary conditions prescribed by the CESM model under the high emission RCP 8.5 scenario are shown in **Figure 17**. Annual cycles of VPD for model grid points high in the Nyungwe Forest and at lesser elevation in Kigali east of the CND both show remarkably little variation in VPD over the course of the century. Owing to the cool, persistently moist highland climate that characterize the CND landscape, the VPD values are consistently low in Nyungwe throughout the year for the three decadal time periods 2009-18, 2055-64 and 2090-99. This contrast significantly with results from Kigali, where VPD registers four times higher than in Nyungwe during the mid-year dry season (20 vs. 5 hectopascal pressure deficit). This represents a favorable outlook over several decades to come for the CND in terms of limiting desiccating conditions that would elevate fire potential, stress crops and rapidly draw down hydrological resources.

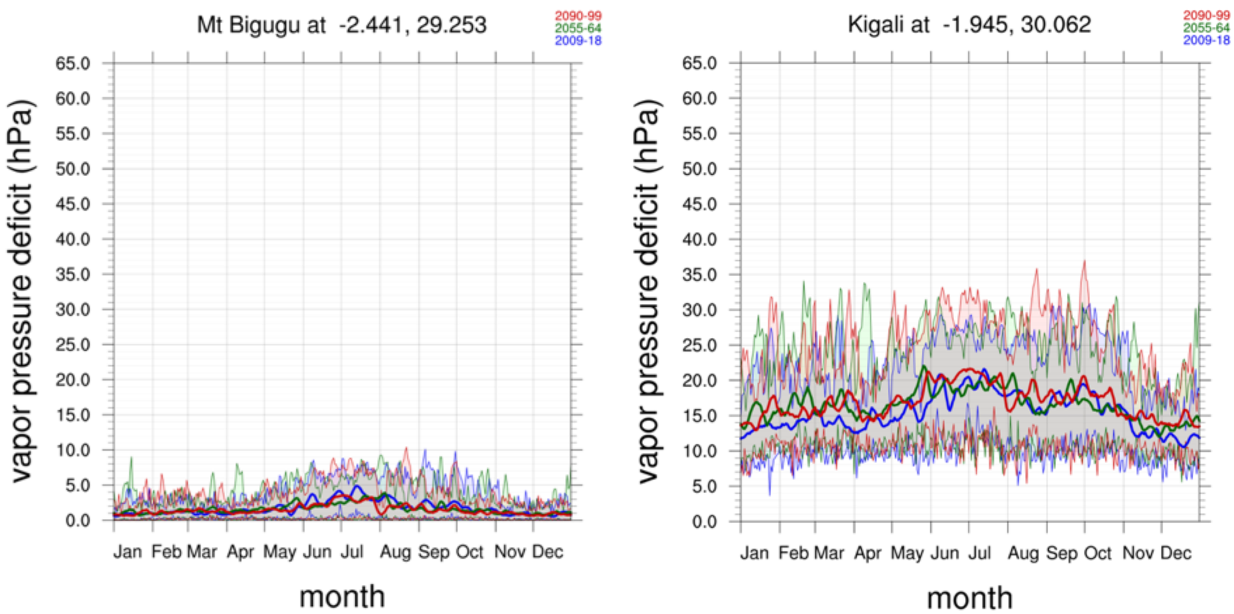

Figure 17. Modeled Vapor Pressure Deficit (VPD) on slope of Mt Bigugu in the Nyungwe Forest (**left**) and Kigali (**right**) for the recent past (2009-18, blue, mid-century (2055-64, green) and late-century (2090-99, red). Source: EAGLE project[38]

3e. Increase in cloud base altitude and fog interception levels

The height above sea level that clouds form in moist, tropical airmasses that characterize the CND region is dictated by a combination of temperature and water vapor content in the planetary boundary layer, the lowest part of the atmosphere. Under warming climatic conditions, the exponential increase in water vapor carrying capacity of air with linear temperature increase results in a rise of the lifting condensation level (LCL), the height of the cloud base. Or, to put it another way, it would take a major increase in boundary layer moisture content to balance the temperature rise and maintain the LCL at present day heights, and such

[37] Seager, R., Hooks, A., Williams, A.P., Cook, B., Nakamura, J. and Henderson, N., 2015. Climatology, variability, and trends in the US vapor pressure deficit, an important fire-related meteorological quantity. *Journal of Applied Meteorology and Climatology*, *54*(6), pp.1121-1141.
[38] EAGLE project, available at https://www.eagleclimate.org/climate/#

an influx of additional moisture is neither expected nor depicted in the majority of climate models. It is highly likely that warming experienced to date along the CND has already had a discernible impact amounting to a rise in LCL of many tens of meters, but this atmospheric variable is generally unmeasured except at major airports since it requires expensive instruments called ceilometers for accurate measurements. Adding to the difficulty in observations is that there is a large diurnal cycle in cloud base height as temperatures respond to the daily cycle of solar heating, causing cloud bases to be relatively low in the mornings and rise considerably to a peak in mid-afternoon.

Under a stable climate, the montane forest ecosystem is well calibrated to the daily and seasonal cycles in cloud base altitude. Numerous species, and epiphytes in particular, depend upon the near-daily immersions in fog[39]. The immersion in fog also deposits moisture directly to vegetation, which then drips to the forest floor. Fog interception is difficult to measure, but is suggested by modeling results to augment annual rainfall by approximately 10% in African equatorial montane forests[40]. The significance of fog interception for moisture provision in tropical montane forests is especially important for sustaining vegetation during dry seasons, when rain shower activity may not occur for weeks at a time[41]. An additional consideration is that mountains taper upwards: in consequence, elevating the zone of precipitation borne by fog deposition decreases the area receiving such enhancement to annual rainfall. This represents a somewhat hidden loss of hydrological inputs as a consequence of climatic warming that have downstream consequences from reduced runoff, and not just within the affected highland ecosystem itself.

Climatic warming is therefore highly problematic to tropical montane forest ecosystems such as the protected forests of the CND. The rising cloud base levels over time are likely to cause die-offs and upward migrations of the lower limit of the range of organisms not adapted to the drier conditions found beneath cloud base.

Also of relevance is that landscape conversion of montane environments through deforestation represents an enhancement of this effect. Lands cleared for agriculture, especially when bare or lying fallow, absorb solar radiation directly at the surface rather than photosynthetically in a forest canopy, so warm the overlying atmosphere far more readily than forested lands. It is therefore to be expected that the deforested landscapes of the CND already exhibit anthropogenic elevation of cloud bases during daylight hours, while extant forests maintain both cooler temperatures and lower cloud base heights

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[39] Villegas, J.C., Tobón, C. and Breshears, D.D., 2008. Fog interception by non-vascular epiphytes in tropical montane cloud forests: Dependencies on gauge type and meteorological conditions. *Hydrological Processes: An International Journal*, *22*(14), pp.2484-2492.

[40] Bruijnzeel, L.A., Mulligan, M. and Scatena, F.N., 2011. Hydrometeorology of tropical montane cloud forests: emerging patterns. *Hydrological Processes*, *25*(3), pp.465-498.

[41] Villegas, J.C., Tobón, C. and Breshears, D.D., 2008. Fog interception by non-vascular epiphytes in tropical montane cloud forests: Dependencies on gauge type and meteorological conditions. *Hydrological Processes: An International Journal*, *22*(14), pp.2484-2492.

Section 4: Some consequences of climate change along the Congo-Nile Divide

This section offers discussion on some key vulnerabilities of the CND landscape of relevance to the proposed CND project and associated activities.

4a. Wildfire occurrence

Wildfire occurrence in forested lands exacerbated by climatic warming is a rapidly mounting concern globally. Climate change is undoubtedly intensifying the potential for forests to burn during periods of seasonal drought, lengthy periods of subnormal rainfall, and often for the most severe cases, a combination of the two. Under such circumstances, the VPD parameter rises to anomalously high levels, driving vegetation desiccation and yielding woody fuels primed for ignition[42].

While there is reason for concern that such factors may become increasingly common along the CND landscape, there are also fairly substantial indications that the overall threat of wildfire may remain relatively low for the foreseeable future. Absence of fire-adapted flora in CND highland forests suggests that fire has not been a major selective force within the forest ecosystem. The 1997 visitation of weeks-long uncontrolled wildfires in the Nyungwe forest had an ecological imprint that remains evident 25 years later, as burned areas revegetated with dense ferns rather than replacement forests[43], representing a net loss of 12% of Nyungwe's forest cover and corresponding loss of its carbon endowment. Despite increased propensity for drying of vegetation as the climate warms, forests remain sufficiently moist such that fire causing forest losses are infrequent, and when they occur are usually tied to anomalous dry spells paired with human ignition associated with illicit human activity in the forest. Such was the case in 1997, which featured a marked climatic anomaly, whereby the normal mid-year dry season extended into October [44] (**Figure 18**).

Normal climatic variability has the potential to produce comparable periods of drought, and a warming climate intensifies the potential for rapid drying of vegetation and forest litter under such conditions. However, the stability of the VPD projections over time, shown above, with a relative balance between intensifying evaporative potential being matched by increasing precipitation delivery (and particularly during the dry season months), suggests that widespread fire occurrence may remain low probability events provided that anthropogenic ignition can be curtailed through vigilance by protected area authorities.

This represents a favorable outlook over several decades to come for the CND in terms of limiting desiccating conditions that would elevate fire potential and also stress crops and rapidly draw down hydrological resources. Importantly, however, not clearly evident in these model outputs is that rising cloud bases and associated warming temperatures increase the rate of drying of vegetation, increasing wildfire risk during rain-free periods, especially in lower reaches of forested terrain bordering settled areas where risks of anthropogenic ignition are highest **(Figure 19)**

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[42] Abatzoglou, J.T. and Williams, A.P., 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, *113*(42), pp.11770-11775.

[43] Masozera, A.B. and Mulindahabi, F., 2012. Post-fire regeneration in Nyungwe National Park-Rwanda. WCS White paper report

[44] Seimon, A., 2012: Climatology and Potential Climate Change Impacts of the Nyungwe Forest National Park, Rwanda. WCS White paper report, Wildlife Conservation Society, New York, USA, 44 pp.

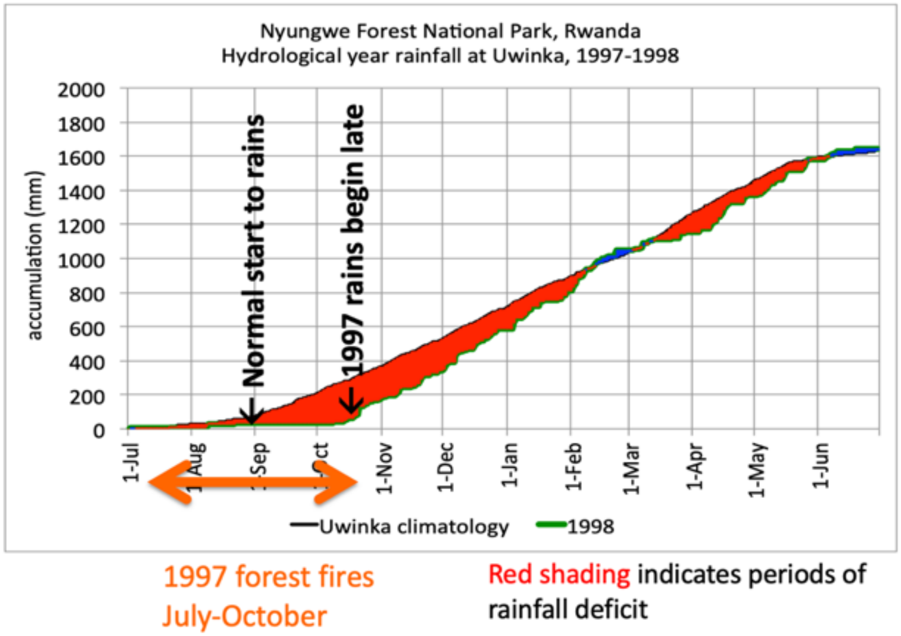

Figure 18. 12-month cumulative rainfall (mm) compared to normal at Uwinka in Nyungwe Forest National Park starting on 1 July 1997 in the mid-year dry season. The anomalously late start to the rainy season was instrumental in forest desiccation, causing the most severe fire episode on record. Source: Seimon (2012)[45]

Figure 19. Smoke plumes from fires inside the margin of Volcanoes National Park in Rwanda in July 2009 resulting from illicit incursions during the dry season. Unlike the Nyungwe fires in 1997, these did not lead to widespread forest loss. Photo courtesy of James Kemsey, International Gorilla Conservation Program.

[45] Seimon, A., 2012: Climatology and Potential Climate Change Impacts of the Nyungwe Forest National Park, Rwanda. WCS White paper report, Wildlife Conservation Society, New York, USA, 44 pp.

4b. Ecosystem range shift potential

Given the large elevational range of CND landscapes, a very important parameter given a warming climate is the environmental lapse rate, the change in temperature experienced as a function of elevation. In the moist tropics of east central Africa, the temperature decreases about 0.55 °C on average for every 100 meters gained above sea level[46]. Therefore, if the CND experiences net warming of +2.6°C (a near-certainty by mid-century, as discussed above), this translates to uphill migration of isotherms – and all temperature-dependent organisms, ecosystems and agricultural practices – by about 473 meters. This has ramifications to environmental futures along the CND particularly for plants, animal species, pathogens and human activities such as choice of cultivars with thermal preferences or specific tolerances.

The pathogen examples presented above are merely indicators of responses by a vast assemblage of biota that may be coerced upward to escape increasingly hostile conditions borne by climate change. This is a broad topic worthy of its own report, so is somewhat beyond the scope of the present review. A comprehensive overview of potential ecosystem range shifts to climate change for the Albertine Rift, which encompasses the CND landscape, based on Maxent species distribution modeling was presented in Ponce-Reyes et al., 2017[47], and includes the notable quotes below.

> "*We found that suitable conditions for most ecosystems are predicted to contract rapidly in extent and shift upwards in altitude. High-altitude ecosystems and the endemic species they support are at immediate risk, owing to rapid predicted shrinkage in their suitable extent."*
>
> *"The extent and structure of boundary zones between the Rift's ecosystems may change significantly through time, due to the contractions and shifts of the environmental conditions for existing ecosystem distributions."*
>
> *"By 2070, 44% of the region could be climatically unsuitable for the current ecosystems. Conservation planning across the Rift will need to account for these ecosystem shifts and rapidly changing boundary zones to ensure the long-term persistence of the many endemic species."*

Among cultivars, both tea and coffee are of particular interest in the CND landscape so are examined in greater detail below.

4c. Tea cultivation

Tea is the world's most consumed beverage after water. Rwanda is one of just a handful of countries where tea is cultivated for export, and although it is only a minor producer in terms of global output, Rwandan tea is valued as being of a high quality. Tea plants show optimal growth in cool, moist highlands environments, and the CND landscape is therefore a primary area for tea cultivation in Rwanda (**Figure 20**).

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[46] Camberlin, P., 2018. Climate of Eastern Africa. In *Oxford Research Encyclopedia of Climate Science*. Link

[47] Ponce-Reyes, R., Plumptre, A.J., Segan, D., Ayebare, S., Fuller, R.A., Possingham, H.P. and Watson, J.E., 2017. Forecasting ecosystem responses to climate change across Africa's Albertine Rift. *Biological Conservation*, *209*, pp.464-472.

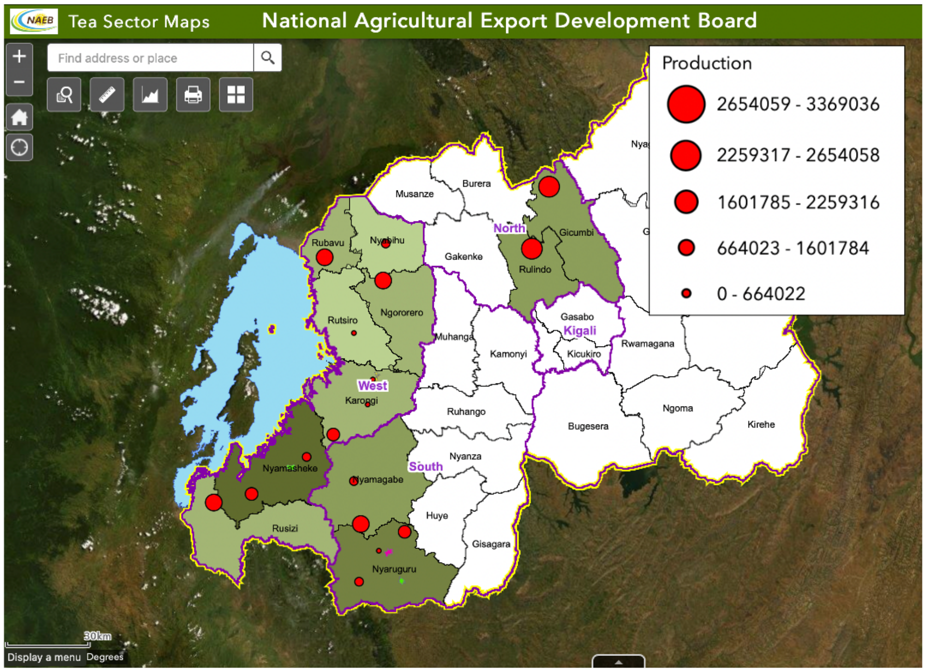

Figure 20. Tea production by district (shading, darker colors have high levels) and by tea factory output (scale provided in kilograms per year. Source: Rwanda National Agriculture Export Board[48]

In common with other producers, the Rwandan tea sector faces a number of challenges related to climate change that must be addressed to ensure its long-term sustainability. Tea production is vulnerable to climate-related events, and thermal increase is believed to already be affecting both yields and tea quality. The optimum temperature for shoot replacement cycle, which allows for frequent harvesting, is approximately 23.5 °C[49]. Among adaptation measures recommended by the UN-FAO are planting drought and stress tolerant tea cultivars, diversifying production, intercropping tea with other tree crops, organic cultivation and investing in water conservation technologies[50]. This points to the desirability of planting tea cultivars with higher optimal temperature thresholds and/or improved ability to access soil moisture through greater rooting depths. Such tea cultivars maintain a higher relative water content and exhibit less decline in photosynthesis under water stress[51].

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[48] Map generated from the National Agriculture Export Board website https://naebcrm.maps.arcgis.com/apps/webappviewer/index.html?id=f8202581a71f4aadba8113858d7aa4e3

[49] Jayasinghe, S.L. and Kumar, L., 2020. Climate change may imperil tea production in the four major tea producers according to climate prediction models. Agronomy, 10(10), p.1536.

[50] FAO: Food and Agriculture Organization of the United Nations, 2022: International tea market: market situation, prospects and emerging issues. https://www.fao.org/3/cc0238en/cc0238en.pdf

[51] Rigden, A.J., Ongoma, V. and Huybers, P., 2020. Kenyan tea is made with heat and water: how will climate change influence its yield? *Environmental Research Letters*, *15*(4), p.044003.

The functional quality of tea is influenced by climate change because concentrations of the methylxanthine caffeine and various polyphenolic catechin compounds are highly correlated with rainfall patterns[52]. Based on observations in Kenya's Kericho district, a remarkably direct relationship had been identified between two climatic variables, temperature and soil moisture, and tea yield. Using the satellite-measured variable, solar-induced fluorescence (SIF) as a proxy for photosynthetic efficiency, Rigden et al. (2020)[53] found it correlated extremely well with tea production (R=0.93), while temperature and soil moisture exhibited the expected inverse relationship (i.e., warming temperature are associated with drier soils). Applying these relationships to projections of future climates from the CMIP5 suite of models yielded an average loss of 5% in yield by mid-century relative to the recent past (range of -12% to +1%), noting that increases in soil moisture from corresponding increases in precipitation significantly reduced the deleterious impacts of temperature increase, which would be twice as large absent the increase in soil moisture. These simulations and result are particular to western Kenya, however; whether they similarly apply to western Rwanda requires further investigation.

Not included in the FAO listing of recommendable adaptation actions[54] is upward translocation of tea plantations to track optimal temperatures, which is a notable omission. The tea plant has a high thermal sensitivity, and for consistent shoot development to occur – critical for harvesting at regular multiday intervals – requires adequate soil moisture be sustained from a combination of regular rainfall and low desiccation rates. Therefore, an obvious adaptation measure would be expansion of tea growing at increasing altitudes in order to track optimal conditions. While this may be an overly simplistic approach, it is notable that a recent review found evidence that tea quality improves as a function of increasing elevation[55].

4d. Coffee cultivation

Rwandan coffee production is based around high value Arabica coffee beans. Much like tea, coffee production is focused in cool, moist highland zones, though with a somewhat warmer thermal range and higher rainfall inputs. Overall, this review finds a surprising lack of studies examining potential climate change impacts upon coffee production, which contrasts considerably with the tea sector. Caution is therefore advised regarding extrapolating coffee production response to climate change accordingly to direct vertical displacements suggested by temperature changes alone.

Specific environmental parameters have been identified as favorable for Rwandan Arabica coffee as follows: elevation 1400– 1900 m.; annual rainfall 1500–1600 mm; temperatures of 18–22 °C; average sunlight of 2200– 2400 hours per year; fine-textured soils >1 m depth with total porosities of 50–60%; pH of 4.5–6.0; moderate-high sums of basic cations; and 2–5% organic

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[52] Ahmed, S., Griffin, T.S., Kraner, D., Schaffner, M.K., Sharma, D., Hazel, M., Leitch, A.R., Orians, C.M., Han, W., Stepp, J.R. and Robbat, A., 2019. Environmental factors variably impact tea secondary metabolites in the context of climate change. *Frontiers in plant science*, *10*, p.939.

[53] Rigden, A.J., Ongoma, V. and Huybers, P., 2020. Kenyan tea is made with heat and water: how will climate change influence its yield? *Environmental Research Letters*, *15*(4), p.044003.

[54] FAO: Food and Agriculture Organization of the United Nations, 2022: International tea market: market situation, prospects and emerging issues. https://www.fao.org/3/cc0238en/cc0238en.pdf

[55] Ahmed, S., Griffin, T.S., Kraner, D., Schaffner, M.K., Sharma, D., Hazel, M., Leitch, A.R., Orians, C.M., Han, W., Stepp, J.R. and Robbat, A., 2019. Environmental factors variably impact tea secondary metabolites in the context of climate change. *Frontiers in plant science*, *10*, p.939.

matter [56,57]. Such conditions are optimized immediately southeast of Lake Kivu on the western side of the CND landscape. Coffee cultivation flanks both sides of the CND landscape, but unlike tea cultivation, does not extend upward very far towards the ridge axis at present due to thermal preferences (**Figure 21**).

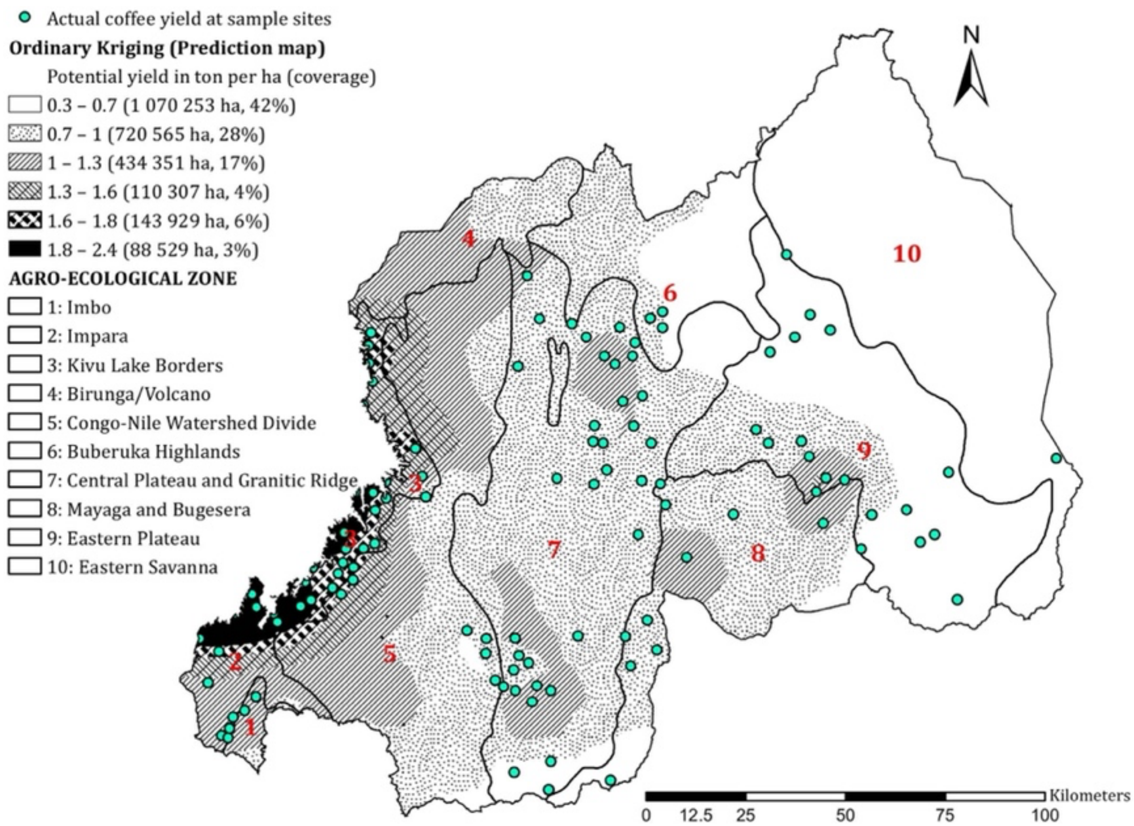

Figure 21. Estimated potential Arabica coffee yield (tons per hectare) predicted in ten agro-ecological zones of Rwanda based on actual yields measured at sample sites. Source: Nzeyimana et al., 2014[58]

Studies on coffee production performed at global scales suggests that Rwanda is potentially the most stable producer of Arabica coffee into mid-century[59] (**Figure 22**), but refinement of such results is needed to accommodate factors beyond straightforward climate parameters.

[56] Verdoodt A, and Van Ranst, E. (2003) Land evaluation for agricultural production in the tropics: A large – scale land suitability classification for Rwanda. Ghent: Laboratory of soil science, Ghent University.
[57] Nzeyimana I, Hartemink AE, Geissen V (2014) GIS-Based Multi-Criteria Analysis for Arabica Coffee Expansion in Rwanda. PLoS ONE 9(10): e107449
[58] Nzeyimana I, Hartemink AE, Geissen V (2014) GIS-Based Multi-Criteria Analysis for Arabica Coffee Expansion in Rwanda. PLoS ONE 9(10): e107449

[59] Ovalle-Rivera O, Läderach P, Bunn C, Obersteiner M, Schroth G (2015) Projected Shifts in Coffea arabica Suitability among Major Global Producing Regions Due to Climate Change. PLoS ONE 10(4): e0124155

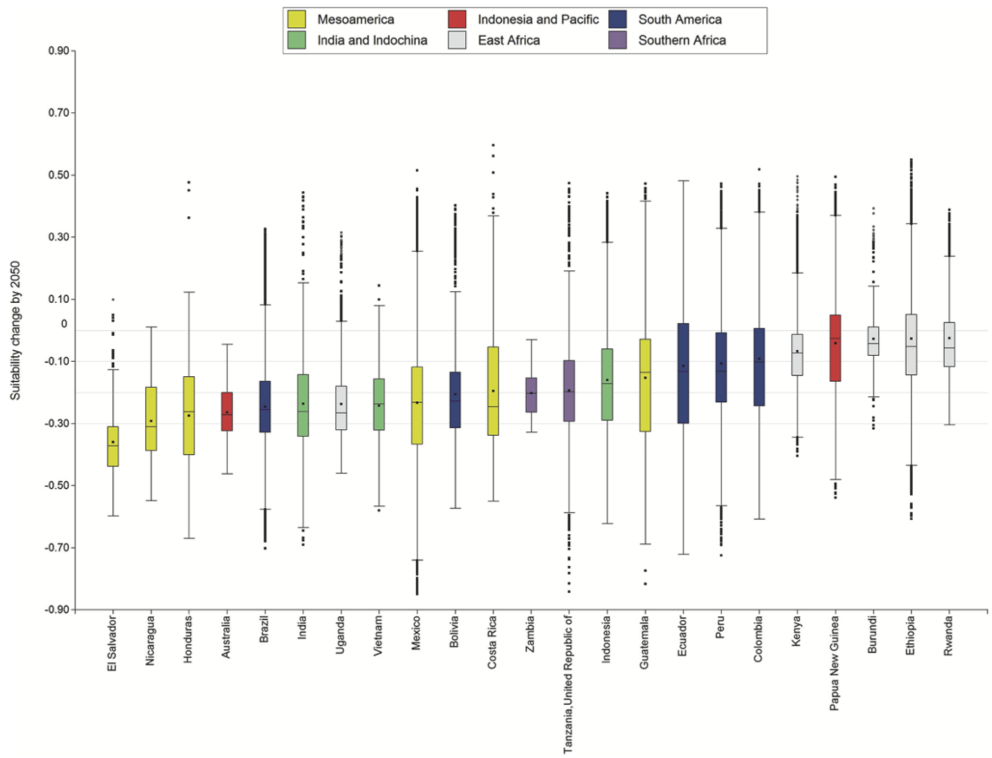

Figure 22. Suitability change in main Coffea arabica growing countries by the mid-21 century. The dot represents the mean, the line the median, and the limits of the boxes are the 0.25 and 0.75 quartiles, while the extremes are the 0.05 and the 0.95 quartiles and the dots beyond the outliers. Rwanda is situated at the extreme right, representing the most favorable outcome under climate change of all countries considered, Source: Ovalle-Rivera et al., 2015

As just one example, coffee cultivation in Rwanda has a particular challenge in the prevalence of the Antestia bug ("stink bug"), which can introduce a flavor often compared to potatoes that greatly diminishes the market value of beans harvested from coffee plants thus affected. And contrary to most agricultural pests, the Antestia bug's prevalence increases as a function of elevation[60][61]. This diminishes prospects for coffee cultivation to elude increasing climatic stress by promotion of cultivation at progressively higher elevations.

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[60] Azrag AGA, Pirk CWW, Yusuf AA, Pinard F, Niassy S, Mosomtai G, et al. (2018) Prediction of insect pest distribution as influenced by elevation: Combining field observations and temperature- dependent development models for the coffee stink bug, *Antestiopsis thunbergii* (Gmelin). PLoS ONE 13(6): e0199569

[61] Bigirimana, J., Uzayisenga, B. and Gut, L.J., 2019. Population distribution and density of Antestiopsis thunbergii (Hemiptera: Pentatomidae) in the coffee growing regions of Rwanda in relation to climatic variables. *Crop Protection*, *122*, pp.136-141.

Section 5: Summary of key climate change concerns

Without strategic actions to confront mounting stresses borne by climate change interacting with unsustainable land-use practices, the CND would doubtless undergo a profound transformation over coming decades with significant loss of biodiversity and ecosystem services, reducing agricultural potential, severe hazards to humanity and loss of livelihoods. Temperature increase and loss of fog immersion will cause desiccation of the lower margins of protected forests promoting die-offs, arrival of pests, pathogens and invasive species, and increasing fire ignition potential. Current cultivation practices of both subsistence crops and valuable cash crops like tea and coffee will be drawn uphill, adding to pressure to convert protected forests to farmland. A summary of some key findings brought to light in this report is outlined in **Table 1**; this is not intended to be an exhaustive list of climate change-borne concerns for the CND landscape, but covers those of greatest relevance to the proposed project's agenda and concerns.

Table 1: Summary assessment of key climate change components and concerns for near-term including the project period, and for the mid-21st century.

Climate component	Character of change	Level of confidence	Near-term concern	Mid-century concern
Temperature	Upward trend from global greenhouse gas emissions and land-use change	Very high for +2.6 °C net increase 1970-2040	Elevational range of biota including pests and pathogens increasingly out of balance	Major uphill displacements of biota including cultivars due to ~473 m rise in thermal conditions
Annual precipitation	Increasing totals	Moderate, but considerable model variation	Low concern, with natural interannual variability still dominant	Moderate concern, with majority of models showing upward trend
Precipitation intensity	Increasing short-period rainfall and storm totals	Almost certain to occur	Severe landslide hazard already present and increasing, building flash flood potential	Extreme hazard: widespread and frequent landslides and flash floods
Cloud base height	Rising cloud base and levels of fog immersion in forests	Likely ongoing, will continue with temperature increase	Already significant in deforested highlands with some loss of moisture provision	Of major concern to forest ecology in protected landscapes
Drought/dry spells	Increasing intensity	Moderate	Some increase in vegetation desiccation potential, possibly enhancing fire risk	Sustained risk of increase in desiccation and fire risk, possibly offset by rainfall increases
Climatic seasonality	Disappearance of mid-year dry season	Low, but explicitly shown in some models	No concern	Increasing convective storm occurrences in June-Aug may eliminate dry season

Whereas climatic changes will act as inexorably mounting stressors, unsustainable land surface conversion and land use practices will greatly exacerbate their impacts. The steep hillsides that characterize much of western Rwanda will experience intensifying erosion and risk of landslides, while built infrastructure such as road and bridges will be overwhelmed since they were engineered to withstand rainfall intensities expected under past climatic conditions that are sure to be exceeded, and with increasing frequency, as time progresses and temperatures steadily increase. Precipitation intensity will increase for short-period rainfall rates and individual storm totals, especially for the fraction of higher-end events that can cause flash flooding and promote landslides. This is certain to occur, is probably already discernible, and likely to amplify very significantly over time as warming progresses. This ties directly to landslides in particular, which already cause high mortality and significant destruction each year, and the CND's elevated vulnerability due to high topographic relief and deforested slopes makes this hazard of paramount concern to address (**Figure 23**).

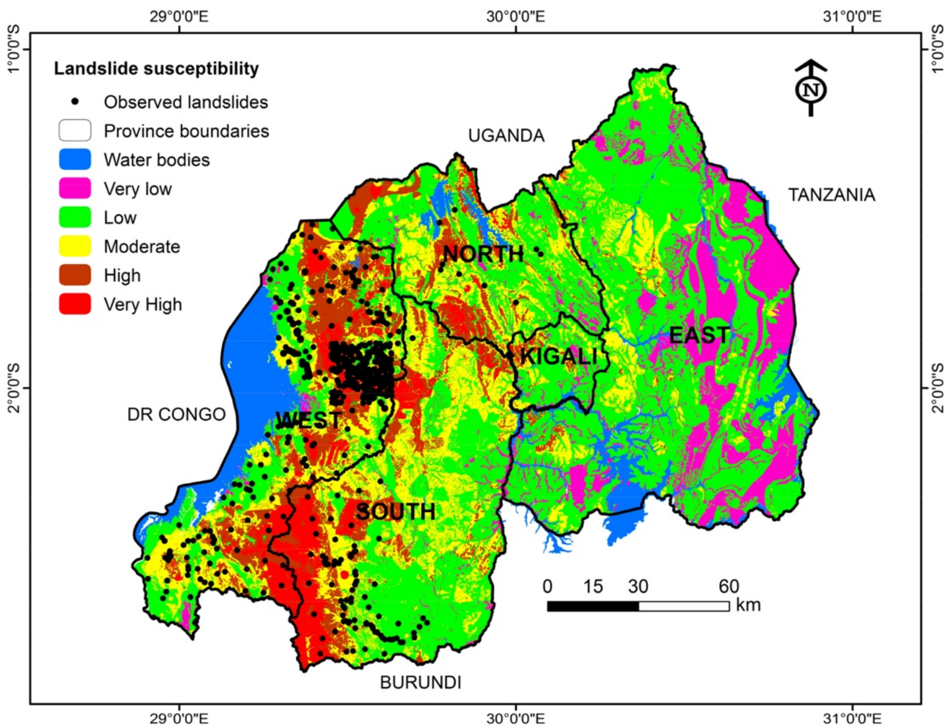

Figure 243. Rwanda landslide susceptibility map showing past observed landslides. Source: Nsengiyumva et al., 2018.[62]

Significant temperature increases are almost certain to continue for decades to come, and will have mounting impacts on both natural and human systems along the CND, and some are already discernible. Over equatorial Africa, observed environmental lapse rates feature temperature decreases by approximately 5.5 °C per kilometer of elevation increase[63], so 2 °C of warming

[62] Nsengiyumva, J.B., Luo, G., Nahayo, L., Huang, X. and Cai, P., 2018. Landslide susceptibility assessment using spatial multi-criteria evaluation model in Rwanda. *International journal of environmental research and public health*, *15*(2), p.243.
[63] Camberlin, P., 2018. Climate of Eastern Africa. In *Oxford Research Encyclopedia of Climate Science*. Link

expected by mid-century translates to a vertical rise on the order of 473 meters, promoting large uphill displacements of a wide range of organisms, ecological processes, cultivars and human activities. While temperatures over the CND region are not expected to rise to levels for heat stress to elevate mortality[64] or reduce labor productivity, the indirect effect of rising temperatures through increased disease incidence is substantial[65].

Western Rwanda is the most productive region in the country for the cultivation of both tea and coffee, where conditions are optimized on the CND's sloping terrain. Both are cash crops with high export value, and are the target of active expansion through both governmental programs and private enterprise. Intensifying environmental stresses from climate change particularly due to thermal increases and the arrival of invasive pests from lowland regions, present challenges both for current plantings and in planning for expansion to new areas; the same concerns apply to other cultivars.

Cloud base altitude, which is highly influential in montane forest ecology and species composition, is likely already elevated above recent past conditions due to conversion of forests to agricultural lands, and certain to rise further in proportion to the degree of warming over coming decades. Ecosystems and species assemblages in the lower reaches of protected forests may already be out of balance with this important environmental variable, and this imbalance will only increase over time, promoting rapid species turnovers, enhance potential for invasives, and act as a strong driver of upward range extensions. Rising cloud bases in concert with warming temperatures also increase drying of vegetation, enhancing wildfire risk during rain-free periods. Fog interception by vegetation also augments montane forest precipitation by an estimated 10%, so rising cloud bases will act to remove this important hydrological input too. Highland forest loss therefore represents a local loss to the ecosystem service of rainwater provision that could be partially restored through reforestation.

Such challenges highlight how essential highland forests are to the climatic resilience of CND communities, for the ecosystem services and products they provide for both the region's vulnerable communities and the national economy. They also recharge aquifers; regulate water flow; control flooding; retain soil; provide wood fuel energy and timber; underpin the country's tourism, which provides the largest contribution to Rwanda's foreign exchange earnings[66]; and provide wider benefits of atmospheric pollution control that sustain the country's economy and the wellbeing of its people[67].

Forest conversion to farmland in the CND highlands has until recently served as a release valve for lowland population pressure at the expense of drastically reduced national carbon stocks, diminished resilience to climate change, enhanced potential for destructive outcomes, reduced ecosystem service provision and disrupted biological connectivity. The resultant loss of ecosystem services and functioning and intensifying environmental stresses borne by climate change now require redirection towards forest restoration and other actions to ensure a sustainable future. Safeguarding the Congo-Nile Divide's remaining highland forests, and setting

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[64] Asefi-Najafabady, S., K. Vandecar, A. Seimon, P. Lawrence and D. Lawrence, 2018: Climate change, population and poverty: vulnerability and exposure to heat stress in East Africa. *Climatic Change*, 148, 561-573.

[65] World Bank, 2022: Rwanda Country Climate and Development Report. World Bank, Washington DC. Link

[66] Rwanda Development Board 2017 Annual Report Link

[67] Andrew, G. and Masozera, M., 2010. Payment for ecosystem services and poverty reduction in Rwanda. *Journal of sustainable development in Africa*, *12*(3), pp.122-139.

long-term goals of reforesting functional linkages connecting them, therefore serve Rwanda's national long-term interests on lessening the severity of impacts of climate change and sustaining critical ecosystem services both locally and downstream, while contributing to global efforts to draw down greenhouse gas concentrations.

Finally, beyond actions to address hazards and stresses outlined above, the CND landscape would benefit from expansion of meteorological monitoring and climatological data collections. The present network of formal monitoring sites in western Rwanda is concentrated along the Lake Kivu shoreline and riverine corridors east of the CND (**Figure 24**). This highlights a need and opportunity to expand monitoring with real-time reporting in most vulnerable areas such as high relief terrain prone to landslides, and near ridgelines where precipitation receipt is maximized.

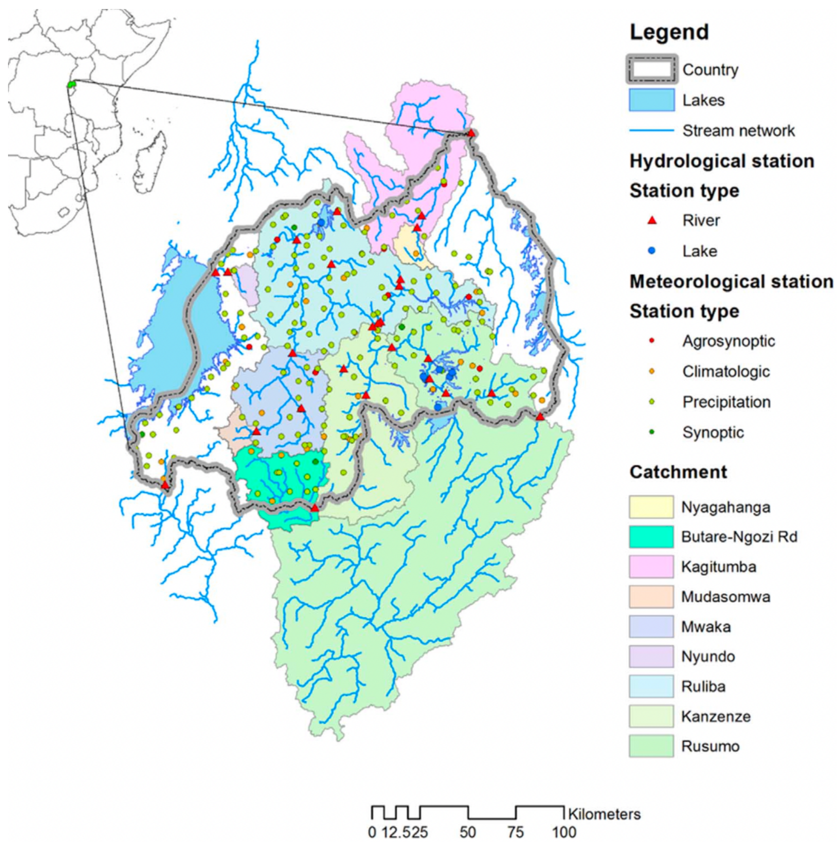

Figure 24. Meteorological and climatological monitoring networks in Rwanda. Source: Abimbola et al., 2017 [68]

[68] Abimbola, O.P., Wenninger, J., Venneker, R. and Mittelstet, A.R., 2017. The assessment of water resources in ungauged catchments in Rwanda. *Journal of Hydrology: Regional Studies*, *13*, pp.274-289.