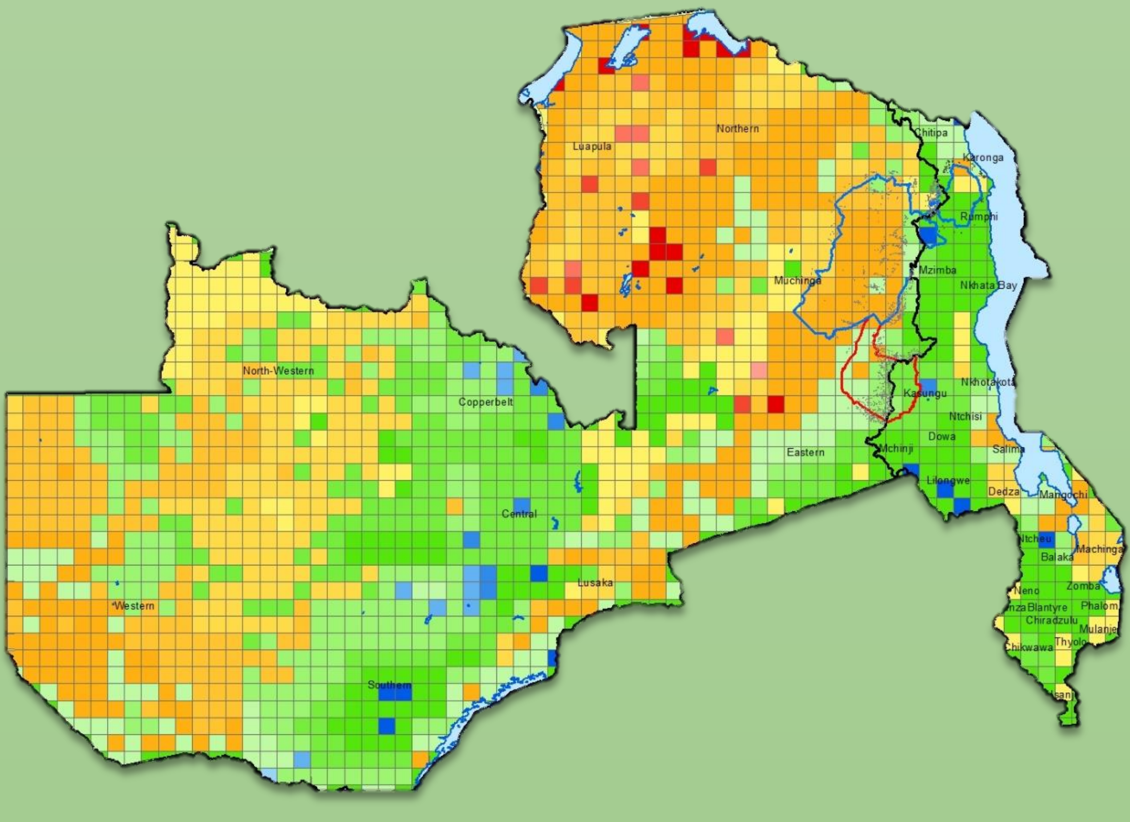
Mapping Climate Risks in the Malawi-Zambia Transfrontier Conservation Area



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For reference, the SADC climate risk assessment work is documented within: Quinn et al. (2020), *Rapid Climate Risk Assessment for the Southern Africa Development Community Region*. SADC Futures: Developing Foresight Capacity for Climate Resilient Agricultural Development Knowledge Series. CCAFS Report. Wageningen, the Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Available online at: ccafs.cgiar.org

Acronyms and Initialisms

C-NRM	Climate Resilience and Natural Resource Management
CSA	Climate Smart Agriculture
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
OPHI	Oxford Poverty and Human Development Initiative
SADC	Southern African Development Community
TFCA	Transfrontier Conservation Area
UNDP	United Nations Development Programme

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Paul Jensen - Rachael Carrie

Executive Summary

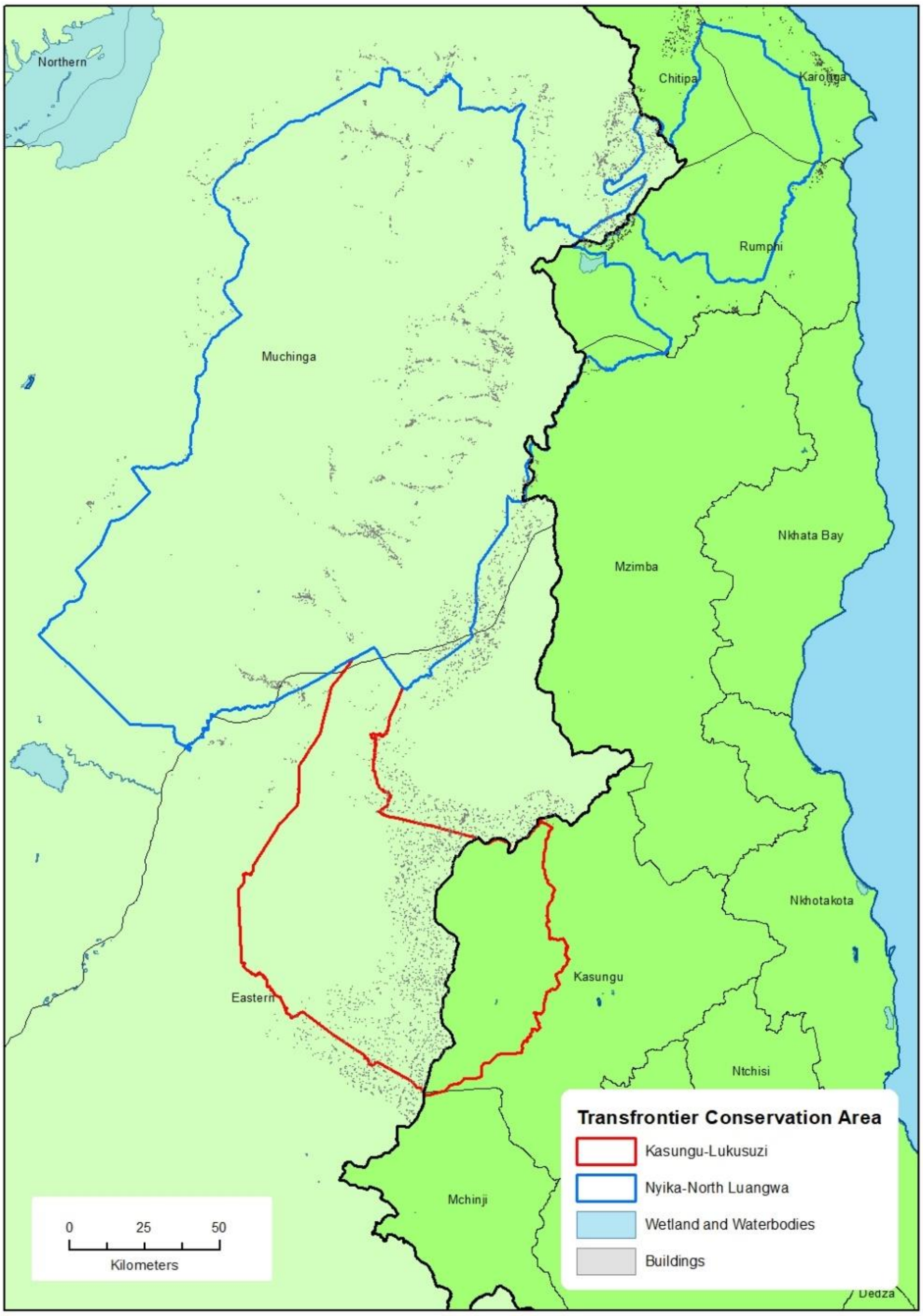
In 2020 a rural livelihood rapid climate risk assessment for the Southern African Development Community (SADC) region was undertaken. The assessment entailed the development of a vulnerability index representing social, natural, physical, financial, and human capital. Data used to represent the capitals were derived from ten indicators, ranging from measures of multidimensional poverty and gender dynamics, through to gross domestic product, annual soil losses and suitability of soils for crop production. To visualise and identify 'hotspots' of future climate risk, the vulnerability index was geographically mapped and combined with future climate projections equating to a world engaged in concerted climate action predicted to result in a mid and end of century mean temperature rise of 1.4°C and 1.8°C respectively (RCP4.5), and a world lacking deliberate climate action with a mid-century mean temperature increase of 2.0°C and end of century mean increase of 3.7°C (RCP8.5). A discussion of resulting climate risk hotspots, deemed to be areas where high vulnerability and climate hazards intersect, was complemented by a systematic literature review of research on agricultural climate risk, adaptation and vulnerability in the SADC region.

Due to the scale of the SADC region, encompassing 16 of the most southern nations of the African continent, the experimental mapping work undertaken in 2020 did not allow easy identification of smaller scale regional climate risk variations or the nuance of vulnerability within nations. As such, a request was made by the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) supported SADC/GIZ Climate Resilience and Natural Resource Management Project to repeat the work with a clear focus on the Malawi-Zambia Transfrontier Conservation Area (Malawi-Zambia TFCA). This focus was necessary to provide a platform for the development of climate risk mitigation and adaption strategies within the Malawi-Zambia TFCA region and the management plans of the area and its key sectors.

Given the significantly different scales of the respective experimental mapping exercises, the suitability of the vulnerability indicator data used in the two studies varied. In the time available to conduct the Malawi-Zambia TFCA mapping exercise, data able to suitably represent and map local governance and financial capital could not be identified or created. Similarly, the data employed in the SADC region study to represent gender inequalities could not be reused in its raw format (being only available at the national level), but in this case a replacement indicator was found in the form of the Gender Development component of the UNDP's Subnational Human Development Index. Following the necessary modifications to the data employed in the SADC region study, the vulnerability assessment of the Malawi-Zambia TFCA was based on six of the original indicators (i.e., accessibility to markets, education, health, standard of living, crop production suitability, and soil erosion) plus the Gender Development Index.

Vulnerability mapping results for the Malawi-Zambia TFCA suggested that there is a distinct difference in average vulnerability across the border region. Malawi was, in general, seen to be less vulnerable than the Zambian border region. Within the TFCA, some of the most vulnerable areas were found to be in the western border area of North Luangwa National Park and the adjoined Musalangu Game

Management Area. An analysis of the underlying vulnerability data highlighted that gender inequalities are higher than in surrounding areas, with general aspects of poverty and distance to market also regularly falling within the higher mean vulnerability scores for the mapped area. In contrast, relatively high gender equality scores were found in the Lukusuzi region, and partly responsible for areas possessing mean scores in the National Park indicating lower overall vulnerability. Higher average vulnerability scores that do exist in the north of the Lukusuzi National Park appear to be a product of relatively high soil loss in addition to being some distance from a market.



Map of Malawi-Zambia Transfrontier Conservation and Research Study Area

(Map layer data source: National/District Boundaries: GADM V4.1; Protected Areas: Peace Parks Foundation Open Data; Buildings: © OpenStreetMap, available under the Open Database Licence)

The mapping of projected climate hazards suggested that by mid-century, rainfall in Kasungu National Park is projected to be relatively high without being extreme in both RCP4.5 and RCP8.5 climate scenarios. Drought is seen to be present in Kasungu National Park for both scenarios, but compared to neighbouring areas the severity of droughts is relatively low. Comparatively, climate projections indicate Lukusuzi National Park may be subject to more severe drought in both projected climate scenarios across all areas, with pockets of higher rainfall found in the very north and eastern border of the park. The Nyika region, meanwhile, is projected to be subject to some of the most extreme rainfall in the mapped area (over 40mm/day). Only the extreme north of Nyika National Park demonstrates potential for drought exposure in either climate scenario. For the Nyika-North Luangwa TFCA sub-component, aside from an isolated pocket of higher rainfall values in the southeast, and in the adjacent Vwaza Marsh Wildlife Reserve, extreme rainfall is not projected for this wider area. However, drought is prevalent across North Luangwa and the adjoined Musalangu Game Management Area, without being projected to reach the severe status found further west outside of the TFCA.

Combining the vulnerability and climate hazard projection data into bivariate climate risk maps, aside from an isolated reduction in climate risk in RCP8.5 from RCP4.5 in northern Lukusuzi National Park, it was found that overall change in climate risk emanating from rainfall was minimal between climate scenarios in the mapped area. Moreover, high vulnerability with high rainfall hazard was not found in the mapped area for either climate scenario in the Malawi-Zambia TFCA and surrounding area. The maps suggested, however, that high rainfall hazards may be present throughout Kasungu National Park, while the area to the west of Luangwa National Park, the adjoined Musalangu Game Management Area, the transition zone to Nyika National Park and within northern Nyika National Park itself, are all subject to medium high vulnerability – high climate rainfall hazard. For drought, medium high vulnerability - high climate hazard is seen through most of Luangwa and the adjoining Game Management Area to the north, with northern Lukusuzi National Park also possessing areas of medium high vulnerability – high climate hazard. Climate risk in the Musalangu Game Management Area of the Luangwa district marginally reduces in the far north, to medium high vulnerability – medium high climate hazard for the RCP8.5 scenario.

The systematic literature review element of the rapid risk assessment led to the identification of 11 articles with data collected in or around the Malawi-Zambia TFCA and with findings specific to the area. The majority of studies centred on arable farming systems, with precipitation hazards discussed most frequently followed by commentary relating to rising mean temperatures and drought. Studies emphasising vulnerability were as prevalent as those focussing on climate adaptation. Of the 11 research articles meeting the search criteria of the evidence review, six presented findings that were relevant to the Nyika-North Luangwa TFCA component and nine to the Kasungu-Lukusuzi component. Collectively, the studies explored climatic impacts on crops, optimized crop planting based on historic and projected climate conditions, the adoption of climate smart agriculture and agroecology, and local knowledge about climate impacts and adaptations. Equality aspects linked to the latter two topics, particularly gender, were considered in six of the reviewed studies.

It was noted in several of the reviewed studies that Climate Smart Agricultural (CSA) systems had the potential to support the region's smallholders in adapting to changing climatic conditions. Studies identified that CSA options combining soil and water conservation management practices, improved maize varieties, and cereal-legume diversification were economically viable and worthy of implementation by smallholder farmers, but cautioned that optimal approaches will depend on spatial and temporal conditions, rather than a 'one-size fits all' approach. Several studies highlighted gender aspects of CSA adoption and the potential inadequacy of gender-neutral strategies for enabling broad CSA uptake. One study notably concluded that climate strategies that improve the equity of decision-making may strengthen the ability to select suitable CSA options and build climate resilience. Studies exploring knowledge of climate dynamics identified inconsistencies between local accounts of weather patterns and meteorological data to highlight the value of different sources of climate knowledge, and to caution against reliance on single sources of information in the development of climate action strategies.

Given this cautionary statement, the results of this climate risk study should be used to provide a starting point for engagement with local Malawi-Zambia TFCA stakeholders prior to the development of climate sensitive management plans for the area. As part of any participatory activities, and before any climate plans are actioned, it is recommended that the findings of the vulnerability mapping exercise undergo some degree of 'ground truthing' via direct in-the-field observation and discussion with local communities and sector leaders. Given the focus on rural livelihoods in this study, a clear understanding of land tenure and specific agricultural activities, including confirming the share and scale of smallholder and larger commercial activities in areas deemed to be climate risk hotspots, is required to determine the potential impacts of future extreme climate events in these areas. Given the omission of a governance indicator in the vulnerability index, developing an appreciation of local governance influences on the development and implementation of climate smart management plans is essential. Likewise, the exclusion of financial capital from the vulnerability index requires that any climate action plan informed by this research requires an additional assessment of local financial vulnerabilities.

1.0 Introduction

This report builds on a rapid climate risk assessment conducted by the University of Leeds in 2020 for the Southern African Development Community (SADC) region (reported in: Quinn et al., 2020). The 'rapid climate risk assessment' research was supported by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and was structured around the Intergovernmental Panel on Climate Change's risk framework, which entails the identification and assessment of climate hazards and the relative exposure and vulnerability of individuals, communities and/or a given region to these hazards (Fig: 1.1). Core to the assessment was experimental mapping work to identify geographic risk hotspots representing the locations of future climate hazards and social and biophysical vulnerability in an agricultural context. Drawing on Thornton et al. (2008), the 2020 SADC project identified 10 vulnerability indicators reflecting natural, physical, financial, social, and human capital. Following normalisation of raw indicator values to a common scale, they were combined into an index of average vulnerability for the region and mapped. The vulnerability index was then combined with future climate projections to 2031-2059 for rainfall extremes and drought hazards (see Section 2.1). Geographic hotspots of potential risk were deemed to be located at the intersection of potential high climate hazard risk and social and biophysical vulnerability. Medium-high climate risks (i.e., medium-high vulnerability and medium-high climate hazards) were found to be extensive across most areas of the SADC region, but most notably to the north (particularly in terms of drought) and the island of Madagascar (in terms of extreme rainfall).

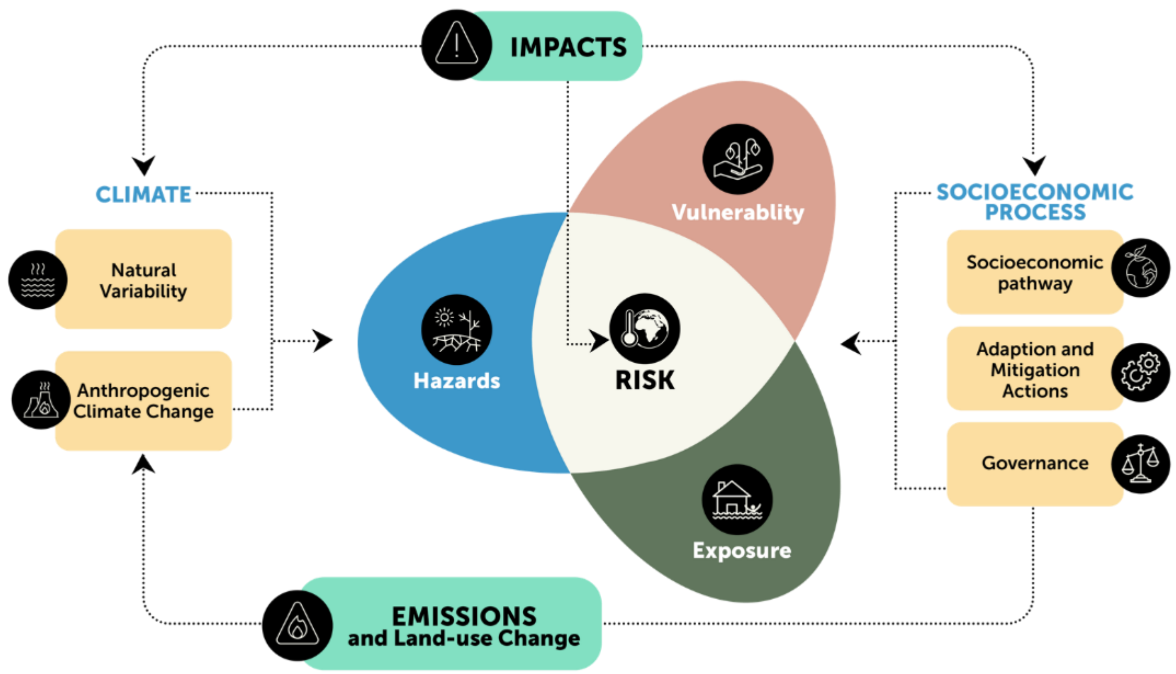


Figure 1.1: IPCC Climate Risk Framework

(Version Source: Quinn et al., 2020; Original Source: IPCC 2014a)

Referencing de Sherbinin et al. (2019), the Quinn et al. (2020) study highlighted several key considerations for undertaking a cartographic climate risk assessment. These included the area the mapping exercise covers, data availability at different spatial scales, and having a clear goal and framework to ensure data is fit for purpose. This final point is subject to further considerations related to the selection or omission of vulnerability indicators and climate parameters, and how and when data is manipulated (e.g., applying weighting to one or more aggregated indicators). Additionally, a key limitation within any mapping exercise, experimental or otherwise, is the availability of data that can be spatially mapped (Jensen et al., 2012). For a climate mapping exercise, this limitation is further complicated by a general lack of future projections and related uncertainties (de Sherbinin et al., 2019). It must also be noted that mapping exercises such as that presented within the SADC region study and herein, which effectively depict a system of actors, activities and interactions, represent a snapshot in time (or an aggregation of snapshots in time) that do not account for the temporal dynamism of a system (Jensen et al., 2012). Any interpretation of a map, or suggested actions guided by them, should be steered by an awareness of this fact and be complemented by further investigation before being acted upon.

In the case of the experimental mapping work conducted by Quinn et al. (2020), both the risk assessment framework and discussion of identified hotspots were underpinned by in-depth literature reviews. Given the scale of the original mapping work, covering all 16 member states of the SADC, the finer detail and nuance of risks that may apply to specific regions was not easy to interpret. Representatives of the SADC/GIZ Climate Resilience and Natural Resource Management (C-NRM) Project therefore requested a repeat assessment focussed on the Malawi-Zambia (Malawi-Zambia) Transfrontier Conservation Area (TFCA) with particular focus on the Kasungu-Lukusuzi sub-component, reflecting the interest of the C-NRM project in TFCAs.

TFCAs are seen as areas that: "*straddle international boundaries* (and) *are a shared asset with the potential to meaningfully contribute to the conservation of biodiversity and the welfare and socio-economic development of rural communities*" (TFCA 2022). Despite the importance of these areas from a range of socioeconomic, political, conservation and broader environmental perspectives, it was noted by C-NRM that climate change impacts are not systematically articulated in the management plans of the Malawi – Zambia TFCA as a whole, nor in the development plans of the main sectors and stakeholder groups. A risk informed development approach for the area was thus deemed desirable.

The C-NRM request to replicate the SADC region experimental climate risk mapping exercise for the Malawi-Zambia TFCA, was intended as a first step toward providing information for a participatory sensitisation stakeholder engagement process focussed on the development of adaptation and mitigation action plans for the area.

The primary objectives of the requested study were threefold:

I. To repeat the SADC rapid climate risk assessment for the Malawi-Zambia TFCA region of Malawi and Zambia based on the methods and indicators described in Quinn et al. (2020).
II. To refine the Malawi-Zambia TFCA analysis and increase the climate risk assessment mapping resolution to focus on the Kasungu-Lukusuzi sub-component of the Malawi-Zambia TFCA.
III. To provide an interpretation of outputs from the spatial assessment and mapping exercise, wherever possible drawing on previous and updated literature searches.

In addition to the original agricultural livelihoods focus of the SADC study, a request was made to incorporate, where data allowed, an appreciation of climate risk to the biodiversity and tourism sectors within the Malawi-Zambia TFCA. Unfortunately, the development of a methodologically robust assessment framework for biodiversity and tourism vulnerability, commensurate with Quinn et al. (2020), proved not to be possible due to the limited time available to conduct this study and lack of suitable secondary data. As such, the focus of the study remained on agricultural and rural livelihoods within and surrounding the Malawi-Zambia TFCA.

Given the above stated limitations of complex mapping exercises and their reliance on robust data, it was acknowledged at the initiation of the study that much of the information used in the assessment of the SADC region may not be available at the spatial resolution required to reveal Malawi-Zambia TFCA climate risks. An attempt was made, however, to replicate the SADC region research as close to its original methods as possible: where the veracity of data was rendered questionable when manipulated for spatial mapping and/or when integrated within the vulnerability index, it has not been included in this study. The detail of changes made to the climate risk mapping approach documented by Quinn et al. (2020) are provided in the relevant sections of this report. As with the rapid climate risk mapping of the SADC region, the maps and any commentary attached to them produced for this study should not be viewed as a definitive climate risk future for the Malawi-Zambia TFCA region. Instead, they may provide useful insight and impetus for promoting stakeholder engagement and guiding discussions for targeted actions.

Herein, Section 2 of the report provides details on how the risk mapping exercise was undertaken, the data employed in the risk mapping assessment, the methods used to update and extend the systematic literature review, and a summary of changes to mapping methods employed in the original SADC region rapid climate risk assessment. Key results of the mapping exercise are then presented in the form of a range of vulnerability and climate projection maps for the Malawi-Zambia TFCA (Section 3). The report then provides a synthesis of recent literature presenting findings about climate hazards, vulnerability and adaptation in the context of agriculture specific to the Malawi-Zambia TFCA and surrounding areas, drawing attention where possible to the hottest areas of climate hazard and vulnerability identified in bivariate hotspot maps (Section 4). The report concludes with a summary of study findings and recommendations for follow-on research (Section 5).

2.0 Approach

2.1 Mapping Context

Zambia and Malawi are neighbouring countries, situated within the interior of the SADC region (Fig: 2.1.1 and 2.1.2). Though possessing regional variations, both countries largely experience a subtropical climate with a dry season and distinct rainy season (November to April) that is influenced by movement of the Inter-Tropical Convergence Zone (WBG, 2022a, 2022b).

Existing climatic hazards in the region include extreme rainfall and drought, which evidence suggests are the most common climate hazards within Africa in recent history (i.e., 1970 - 2020) (CRED, 2020). This is important given the role small-scale rain-fed agriculture plays in much of the region's socioeconomic wellbeing: cultivation in Malawi is largely subsistence-based and critical to the country's food security, with less than 5% of farmers utilising irrigation (see Stevens & Madani, 2016).

Marginally less than a third (32.1%) of Zambian land is engaged in agriculture (incl. livestock rearing), compared to almost 60% of Malawian land (World Bank, 2022). However, central and western Zambian regions are already relatively drought prone (Wolski et al. 2020), with much of its existing agricultural activity concentrated in the south and east of the country. The Eastern district, home to the Lukusuzi National Park and Kasungu border, is also currently home to the production of a range of staple crops and significant livestock rearing as well as being identified as susceptible to changing climatic patterns (see EEL, 2021).

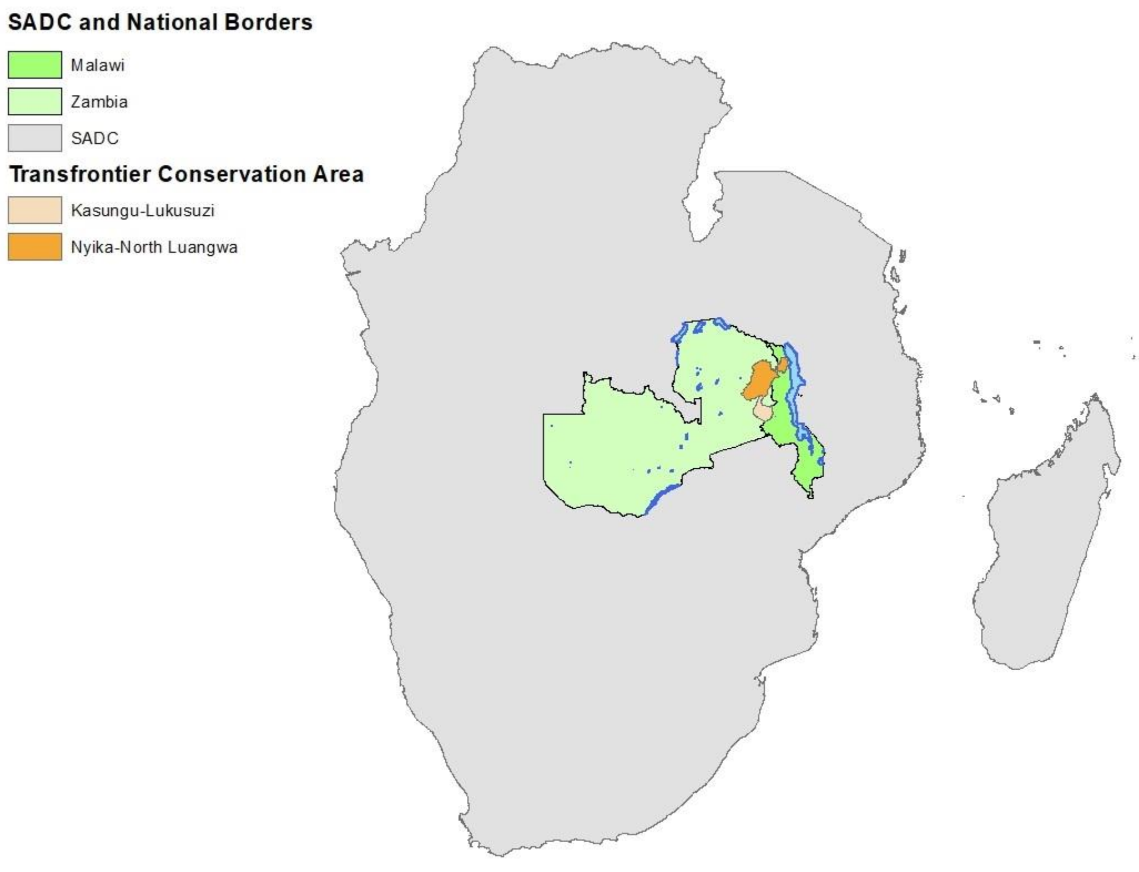


Figure 2.1.1: Location of Malawi and Zambia within the SADC

(Data source: Malawi-Zambia Districts: GADM V4.1; TFCA Protected Areas: Peace Parks Foundation Open Data)

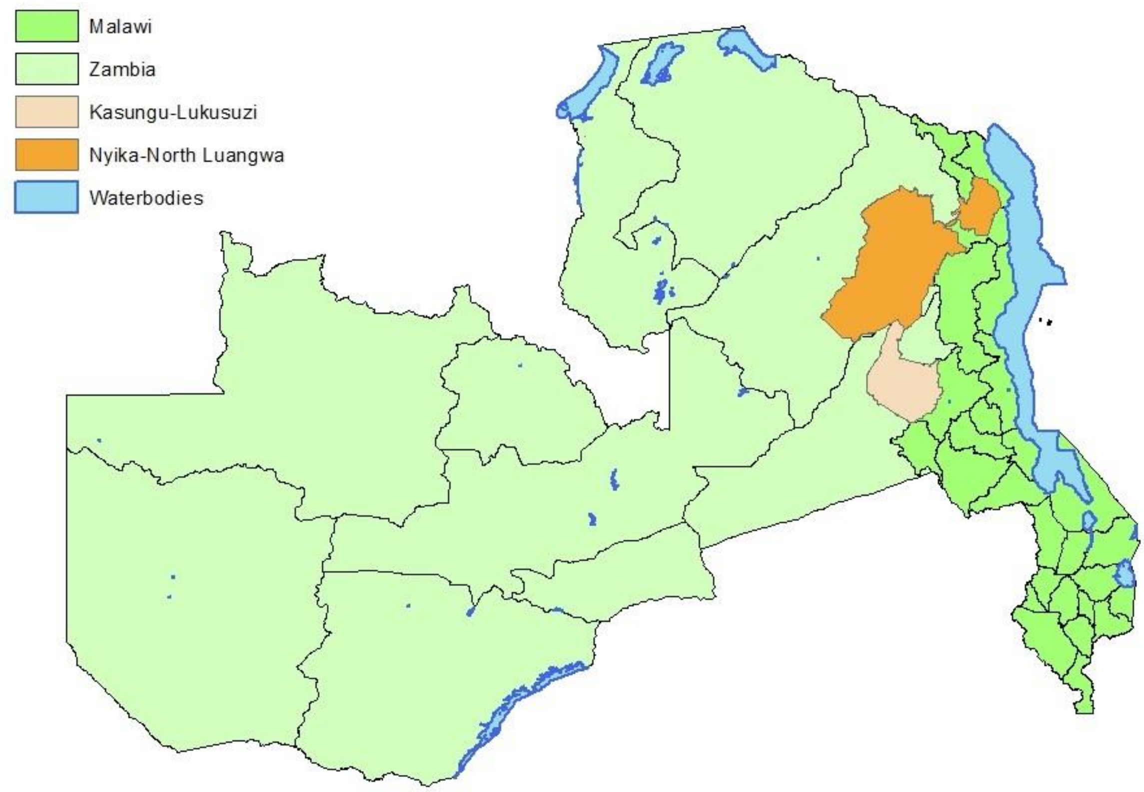


Figure 2.1.2: District Map of Malawi, Zambia and the TFCA

(Data source: Ibid)

Based on 2019 Copernicus Land Cover mapping, Figure 2.1.3 suggests that significant agricultural activity appears to be highly prevalent adjacent to the national parks of the region that are home to significant swathes of protected open woodland and forest, in many places creating a biological 'hard edge' effect. The livelihoods of communities living in these areas are heavily reliant on agriculture (both arable and livestock rearing)[1], in addition to non-timber and timber forest products and tourism. There is concern that climate change may risk inappropriate land management practices and expansion of agricultural lands, with impacts on biodiversity and ecosystem services, if communities are unable to adapt.

Based on spatial analysis of the land cover *within* the mapped TFCA boundary, only 3.6% of this land is categorised as cropland. A notable proportion of this figure is, however, concentrated directly within the relatively small (compared to North and South Luangwa) central belt of the Nyika National Park and within the corridor of land between the Lukusuzi and Kasungu national parks[2]. Many of the region's current agricultural climate risks are shared with the tourism sector and the protected areas of the TFCA (see Fig. 2.1.4). For example, increasing climate driven drought, combined with or without increased wildfires and deliberate burning, can negatively impact the integrity of existing vegetation and lead to potential deaths and/or migration of animals to new areas (EEL, 2021).

[1] For context, in 2017-2018 almost 350,000 households were engaged in agricultural activities including significant (largely male led) livestock rearing in the Eastern district of Zambia (Umar, 2021), while 70% of Malawi's significant total area of agricultural land is farmed by ~3.1 million smallholders under customary tenure (with large estates mainly producing tobacco, tea and sugar and being responsible for 10% of agricultural employment) (CCARDESA, 2022).

[2] Based on spatial analysis of land cover maps for the region (Fig. 2.1.3), 10.1% of Nyika National Park is cropland, with 14.4% of the corridor of land between Lukusuzi and Kasungu national parks being cropland.

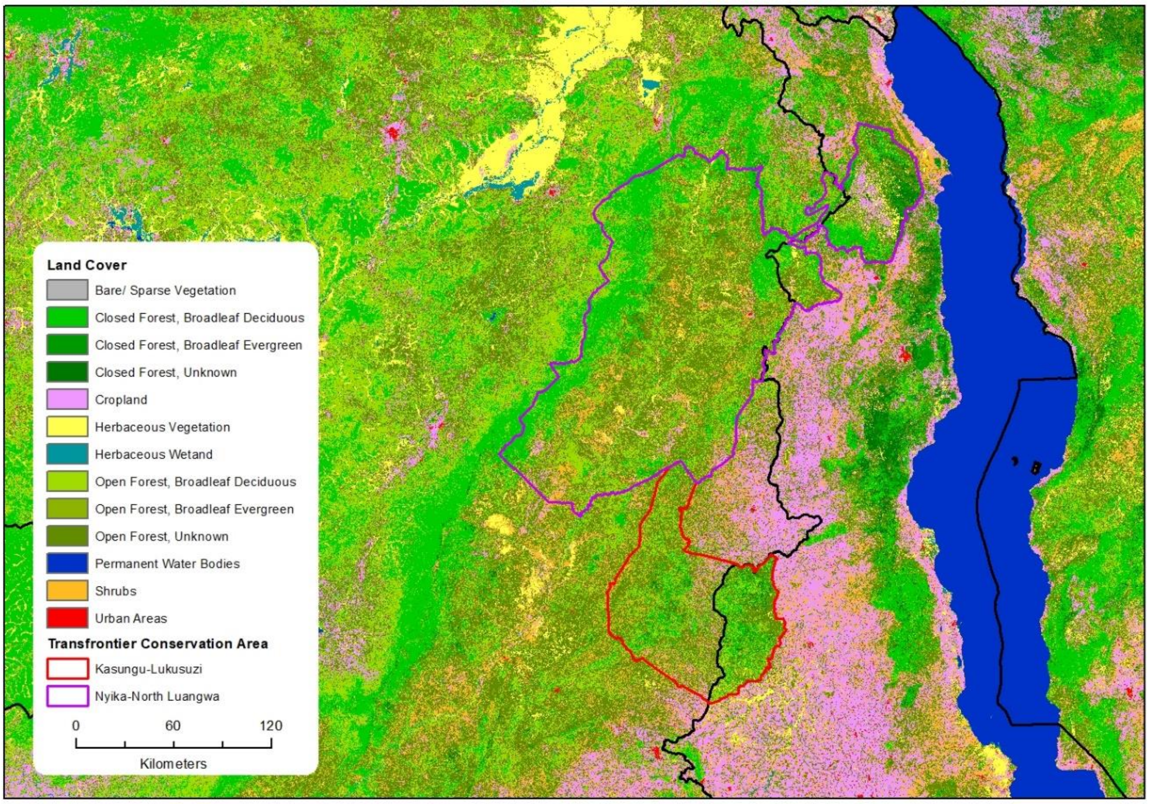


Figure 2.1.3: Malawi-Zambia TFCA Land Cover Categorisation

(Data sources: National Boundaries: GADM V.4; Land Cover: © Copernicus Service Information 2019)

The Lukusuzi and far South Luangwa tourism sector has already been described as vulnerable to the high temperatures and associated droughts that affect the region's agricultural sector (EEL, 2021). Similarly, Malawian forest cover has already significantly diminished due in part to agricultural expansion and has been identified as at risk from increased drought (USAID, 2021), with extreme rainfall being another significant hazard. Both South (and particularly) North Luangwa tourism activities are deemed susceptible to flooding and extreme rainfall (EEL, 2021).

Extreme rainfall can lead to landslides and soil erosion (Chapman, et al., 2021), with floods causing direct injury and death to people and, from an agriculture perspective, livestock; as well as damaging infrastructure and fields (e.g., Sonwa et al. 2017). In terms of the mapping exercise and resultant maps produced for this study, it is noted that extreme rainfall is a necessary but not sufficient condition for damaging floods; land use patterns, drainage and waste management infrastructure are also important determinants. With increasing rainfall however, flood risk intensity can be generally expected to increase (Tazen et al. 2019).

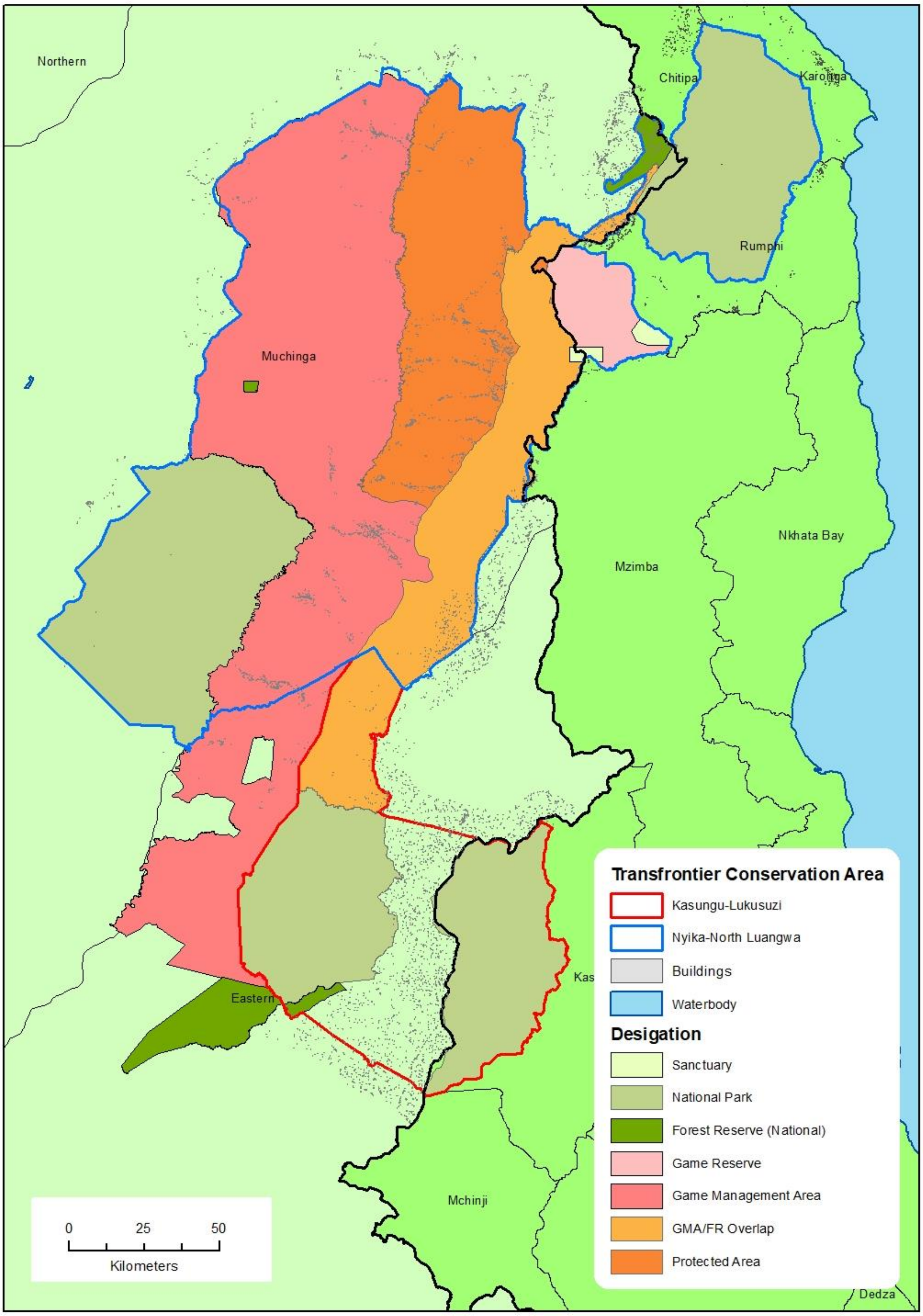


Figure 2.1.4: Map of TFCA and Protected Area Designations

Note: buildings in the TFCA and within 10km of the national parks and other protected areas were mapped to highlight their proximity and potential interaction with local communities. For reference, the areas covered by the Malawian Game Reserve and Zambian Game Management Area are collectively designated as a hunting block.

(Data source: National Boundaries: GADM V4.1; Protected Areas: Peace Parks Foundation Open Data; Buildings: © OpenStreetMap, available under the Open Database Licence)

2.1 *Climate Hazards*

For this study, the RCP4.5 and RCP8.5 future climate scenarios were employed as the reference points for potential climate hazards. In broad terms, RCP4.5 and RCP8.5 are 'Representative Concentration Pathways' measured in W/m^2 (i.e., $4.5W/m^2$ and $8.5W/m^2$) and encompass future atmospheric greenhouse gas concentration scenarios, as described by the IPCC (IPCC, 2014b). RCP4.5 is a scenario linked to continued climate action and implementation of policies to promote a transition to a low-carbon future and a stabilisation of current climate change. In contrast, RCP8.5 is a scenario that represents a world that lacks any deliberate or concerted climate action. Summarising the impact of the two scenarios, for both RCP4.5 and RCP8.5 there is *high confidence* that mean global surface temperature is *likely* to exceed 1.5°C by the end of this century. There is *medium confidence* that the change in surface temperature is *more likely than not* to exceed 2°C in the RCP4.5 scenario. However, for the RCP8.5 scenario, there is *high confidence* that warming will *likely* exceed 2°C (Ibid). Relative to temperatures witnessed from 1986 – 2005, for the relatively near-term period of 2046 - 2065, mean temperature rise for the RCP4.5 scenario is likely to be 1.4°C, with a range of 0.9°C – 2.0°C. RCP8.5 is likely to experience a mean 2.0°C rise, with a range of 1.4°C – 2.6°C. By the end of this century, it is considered likely that the overall mean temperature rise for the RCP4.5 and RCP8.5 scenarios will be 1.8°C and 3.7°C, respectively (Ibid).

The climate hazard data depicted in the maps presented in this report were sourced from the existing map layers produced for the SADC region Rapid Climate Risk Assessment study (Quinn et al., 2020). Notably, in reference to one key limitation of climate risk mapping referenced in the introduction, the climate hazard layers used by Quinn et al. (2020) *do* represent future climate projections. To produce these data layers, Regional Climate Models (RCM) were sourced from Cordex-Africa (see Cordex, 2022). Extreme rainfall and drought hazard data for the RCP4.5 scenario was produced using a multimodal ensemble of 7 RCMs and 9 different Global Climate Models (GCM). For the RCP8.5 scenario, 6 RCMs and 11 different GCMs were employed[3]. 1971 – 1999 was used as the historical data reference point and the period 2031 – 2059 as the mid-century period. Extreme rainfall was assessed by looking at the 95th percentile of daily rainfall. For drought, the Standardized Precipitation Evapotranspiration Index (SPEI) was employed (see: Vicente-Serrano et al., 2010). 1955 – 1970 was used as the reference period and looked at droughts over 1 month and used the log-logistic distribution. Calculation of drought and extreme drought were performed using the 'SPEI' package for the R statistical software (see: Begueria and Serrano 2017; R Core Team 2013). The projected climate model data were embedded in netCDF files and converted to GeoTIFF format for ease of mapping.

2.2 *Vulnerability Indicators*

Vulnerability can be seen as the propensity or predisposition (for someone or something) to be adversely affected (by someone or something). The term is highly contextual, covering a range of concepts and elements, including "*sensitivity or susceptibility to harm and lack of capacity to cope and adapt*" (IPCC, 2104: 128). Both this and the original climate risk mapping study are focused on people and were shaped by considerations of poverty and its relationship to vulnerability. As noted by the Oxford Poverty and Human Development Initiative (No Date), however, people experience poverty much more broadly than simply lacking money. This necessitates a consideration of a range of indicators to characterise human vulnerability. The same is true of biophysical vulnerabilities that people rely on for food, fuel and shelter and/or interact with in another way. Based on the approach of Thornton et al. (2008), Quinn et al. (2020) developed a set of vulnerability indicators reflecting sustainable rural livelihoods human, physical, social, financial and natural capital assets (Carney, 1998).

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[3] A matrix depicting the specific ensemble of RCM/GCMs can be found in Quinn et al. 2020.

For the SADC region study a total of 10 indicators were chosen. For this study, with its focus on the Malawi-Zambia region and its national parks, data of a suitable spatial resolution was found for only 7 indicators. These indicators are summarised in Table 1 and along with any omissions or additions that have been made to the original indicators used. The reader is referred to Quinn et al. (2020) for a detailed description of each indicator.

Table 1: Description and Source of Vulnerability Indicator Data

(Adapted from: Thornton et al., 2008; Quinn et al., 2020)

Capital	Indicator	Description	Data Source: Quinn et al., 2020	Data Source: Malawi-Zambia Study
Human	Education	The subnational poverty headcount for the 'Education' dimension of the OPHI Multidimensional Poverty Index	OPHI (2019)	OPHI (2021)*
	Health	The subnational poverty headcount for the 'Health' dimension of the OPHI Multidimensional Poverty Index. Higher health poverty headcounts are considered to be associated with higher levels of vulnerability.	OPHI (2019)	OPHI (2021)*
Physical	Standard of Living	The subnational poverty headcount for the 'Standard of Living' dimension of the OPHI Multidimensional Poverty Index. A lower standard of living is considered to equate to higher levels of underlying vulnerability	OPHI (2019)	OPHI (2021)*
	Accessibility to Markets	A continuous index based on travel time to urban areas with populations exceeding 20,000. Being in close proximity to a market is considered to be associated with reduced vulnerability	IFPRI (2016)	IFPRI (2016)
Social	Gender Development	Subnational index taken from the Human Development Index (HDI), based on gender development The GDI measures gender development across 3 dimensions, namely: Life expectancy, Mean years of schooling and Command over economic resources Lower scores on the GDI are considered to be associated with higher levels of vulnerability.	Not used (see below)	GDL (2019)
	Gender Inequality	National-level index based on gender inequalities across 3 aspects, namely: Reproductive health, Empowerment and Economic status, taken from the Human Development Index (HDI)	UNDP (2018)	Not used (see below)
	Governance	National-level data on voice and accountability, and government effectiveness	World Bank (2020)	Not used (see below)

Capital	Indicator	Description	Data Source: Quinn et al., 2020	Data Source: Malawi-Zambia Study
Financial	Per Capita GDP	National-level data for per capita GDP, in USD	World Bank (2020)	Not used (see below)
	Agricultural GDP	National-level data for agricultural GDP as a percentage of total GDP	World Bank (2020)	Not used (see below)
Natural	Crop Production Suitability	Categorised from 1-8, where pixels scored 8 are considered areas with high crop suitability (requiring intermediate inputs). It is assumed that higher cropping suitability is associated with lower vulnerability	FAO (2007)	FAO (2007)
	Soil Erosion	An assessment of soil loss for 2012 (Pg yr-1), normalised for the Malawi-Zambia region into quantiles. Soil degradation can undermine agricultural productivity and reduce water quality. Areas with higher levels of soil erosion are considered to be more vulnerable.	ESDAC (2019)	ESDAC (2019)

* Though the 2021 Multidimensional Poverty Index database was consulted and used for this study, it should be noted that the underlying data employed in the Malawi and Zambia 2021 MPI derive from in-country surveys conducted in 2015-16 and 2018 respectively, and are the same as those used in the previous study.

As shown in Table 1, the indicators used in the original SADC region study to characterise human, physical and natural capital were largely reused in their original form in the current study. However, modifications to the indicators of social and financial capital were required.

Social Capital

Within the SADC region study (Quinn et al., 2020), the vulnerability indicators employed to represent social capital were based on the Gender Inequality Index (GII) (UNDP, 2018), and indicators of national Governance relating to accountability and effectiveness. For the current study, it was not possible to use either indicator due to neither being available at the subnational level in their raw format. Including what would be binary figures (i.e. one figure for each nation) in maps produced by allocating regional vulnerability indicators to quartiles is not advisable, and any attempt to create methodologically robust quartiles from these figures using data interpolation would be challenging and beyond the resources of this rapid climate risk assessment.

While a suitable subnational measure of local governance could not be found, a specific request was made by the project host to incorporate an appreciation of gender within the Malawi-Zambia TFCA climate risk assessment. As such, an extensive search and appraisal of alternative indicators to the GII was conducted, with the Gender Development Index (GDI) ultimately chosen because (like the GII) it is produced as part of the UNDP's Human Development Index and the data are recent (i.e., 2019) and publicly available at the subnational level for both Malawi and Zambia.

The GDI measures gender inequalities across three dimensions, namely life expectancy, expected and mean years of schooling and command over economic resources (UNDP, 2020). It is acknowledged that the GDI has received criticism in terms of its ability to be used as a metric of gender inequality, particularly with regards to modelled assumptions about life expectancy and wage division between males and females, and broader misinterpretation of what the index actually infers (Klasen, 2007; Klasen and Schűler, 2011). However, the technical notes to the production of the GDI demonstrate that these concerns were considered within the calculation of the later and current version of the GDI (UNDP 2020). It is further acknowledged that there is some overlap in some of the detail included in the GDI with the indicators used to represent human and physical capital. However, inclusion of the GDI provides some important weighting toward gender development issues. For example, referring to the access to command of resources element of the Index, women generally have less access to, and control over resources, which undermines decision-making capabilities and ability to cope with and adapt to climate impacts (World Bank, 2009).

Good governance creates enabling environments for investment, job creation and effective implementation of regulations, such as those related to climate adaptation, and it is assumed that good governance equates to lower levels of vulnerability. The omission of a governance indicator from the vulnerability index used in this assessment should not be overlooked. Efforts should be made to explore and incorporate local governance considerations across the Malawi-Zambia TFCA within any consultations or actions related to the use of the outputs of the climate risk mapping presented here.

Financial Capital

For the SADC study, the financial capital indictors used were national-level GDP and the proportion of national GDP derived from agricultural activity. These data are not available at the subnational level and it was not possible to source appropriate replacement data. As with the governance indicator, the omission of financial vulnerability information from our index is important, and should not be overlooked. Every effort should be made to consider local variation in financial vulnerability when outputs of the mapping exercised are used.

2.3 Creating Risk Maps

To visualise the relative vulnerability of the Malawi-Zambia TFCA region, data for all indicators were mapped using an ArcGIS Geographic Information System (GIS). The data were imported into the GIS either in its raw tabulated form (e.g., for the MPI and GDI derived indicators) or, where available, in its original GIS format (e.g., the Distance to Market and Soil Erosion data are publicly available as raster map layers). Publicly available map layers for the Malawi and Zambia national borders and the boundaries for 1st and 2nd level districts and national parks were also imported into the mapping environment. Using the *Join – Relate* function of the GIS, data for the district level human, physical and social capital indicators were assigned to the relevant district layers. To incorporate greater resolution into the maps and a consistent data sampling size for vulnerability point data (i.e., for soil suitability, soil loss, distance to market, rainfall and drought), a data sampling grid layer was also produced and employed. To achieve the greatest resolution possible, the smallest practicable grid system was created that would contain at least one datum – this resulted in a data sampling grid of 23km x 23km (with a cell size of 529km^2). The vulnerability data allocation process was repeated and data for all indicators were assigned to the grid layer. This resulted in the creation of seven map layers for each indicator employed in the study (as described in Table 1).

To determine the relative vulnerability across the Malawi-Zambia TFCA and the focus region of Kasungu-Lukusuzi, absolute indicator values were normalised to make them comparable before being combined into an index of average vulnerability. To achieve this, the separate map grid layers for each vulnerability indicator were combined into a single layer with combined 'attribute table', which was then exported to MS Excel. Within Excel the quartile range for each indicator was determined and figures were reassigned to a quartile depending on whether they fell within the 1st, 2nd, 3rd, or 4th quartile of all values. The assignment of values to the 1st or 4th quartile was based on whether a high figure for a given indicator was deemed to be good or bad, and vice versa (e.g., for Soil Loss, high loss was deemed to be bad and was consequently assigned a value of 1, i.e. the 1st quartile; conversely GDI was deemed to be good if falling within the upper 25% of values and assigned a value of 4, i.e. the 4th quartile). Following the raw data processing, each indicator quartile, within each cell of the mapped region, was summed and divided by the total number of indicators to provide an average (the arithmetic mean) level of vulnerability on a continuous scale of 1.0 – 4.0 (representing each quartile). Relative to the mapped region, a score of 1.0 is seen as highly vulnerable, with a score of 4.0 being, in relative terms, minimally vulnerable.

The normalised indicator data for each grid cell, and the combined average indicator value for each grid cell, were imported back into the GIS as a data table and, using the *Join – Relate* function, re-assigned to the 23km x 23km grid layer created in the initial data preparation session. This allowed a choropleth (or 'thematic') map to be produced showing the average indicator vulnerability of Malawi, Zambia and the Malawi-Zambia TFCA. Following this, simple raster layers were produced for each future climate rainfall and drought scenario (i.e., RCP4.5 and RCP 8.5) and overlain onto the vulnerability map before being made semi-transparent and edited to only show rainfall and drought above mean predicted levels through to extreme predicted levels (as shown in Section 3.1).

As with the SADC rapid climate risk mapping study, this exercise was somewhat insightful and identified areas of potential interest for further exploration. However, it once again proved difficult to identify more extreme areas of rainfall and drought. As such, bespoke bivariate maps were produced simultaneously depicting both average vulnerability and climate hazards. To achieve this, the climate data raster layers were converted to data points and normalised in the manner as described above for raster based vulnerability data. The point data for climate risks were then assigned to the 23km x 23 km grid layer (and averaged where multiple points fell within one cell). To produce the discrete figures required to produce a bivariate map (i.e. 1, 2, 3, 4 rather than 1.0 – 4.0) both the average climate risk and vulnerability data was rounded up or down to its nearest significant figure. This heightens the severity, good or bad, of indicators, which <u>should be noted</u> in respect of any interpretation of maps. However, this process also brings greater emphasise to potential hotspots of extreme risk (when compared and contrasted across the Malawi-Zambia region).

2.4 Systematic Evidence Review

Agricultural Sector

Building on Quinn et al., (2020), a systematic literature review was expanded temporally and refocussed spatially to synthesise existing knowledge about climate risk, adaptation and vulnerability in an agricultural context in the Malawi-Zambia TFCA region. We adhered to same methodological guidelines for systematic reviews as outlined in Quinn et al., (2020), namely the 'Preferred Reporting Items for Systematic review and Meta-Analysis Protocols' (PRISMA-P) (Moher et al., 2009). Review details are reported below in line with Berrang-Ford et al. (2015), who tailor reporting requirements to climate research.

Review aim/questions

Explicit aim/objectives and prevailing literature/concepts:

The review is located in the same context of vulnerability, climate hazards and risk mapping outlined previously (Quinn et al., 2020). It aimed to identify literature related to agricultural climate risk in and around the two components of the Malawi-Zambia TFCA guided by the following question: What are the key climate hazards linked to agriculture, and how and where do they interact with vulnerability and adaptation within and in close proximity to the Malawi-Zambia TFCA?

Data source and document selection

The data was sourced and selected in three phases. Firstly, literature for the countries of Malawi and Zambia were extracted from the dataset compiled by Quinn et al., (2020) during their systematic review of literature published about the SADC region between 2016 and 2020. Secondly, after updating the search string to include literature published between 2020 and 2022, and replacing the SADC geographical search terms to focus on the Malawi-Zambia TFCA region, the search was repeated (as detailed in Table 2). Finally, the original 2016-2020 search was repeated with geographic identifiers replaced by those used in the second phase. This was done to ensure we didn't miss any literature published between 2016 and 2020 but added to the database later, or literature identified only by Nyika North Luangwa or Kasungu-Lukusuzi identifiers. The final phase didn't yield any additional literature.

The initial Quinn et al. (2020) systematic search was undertaken on May 5th, 2020 by one researcher. The second and third phases of the search were conducted on June 10th 2022 by the same researcher. Three researchers completed subsequent screening and coding for the first phase of the search, and one of those researchers for the second and third phases. Literature that appeared in more than one of the search phases was removed from the numerical results. All search phases were limited to peer-reviewed literature written in the English language.

Literature source (justification and description): All phases searched the SCOPUS and Web of Knowledge databases. They were chosen because they contain a substantial collection of relevant research, and because they perform precisely and reproducibly when using an extensive Boolean search string (Gusenbauer and Haddaway, 2020).

Search terms and process and selection criteria: Literature from all search phases was selected, screened, and coded following the process, criteria and search strings outlined below and in Table 2.

During the first phase, all literature presenting studies conducted in Malawi (45 research articles) and/or Zambia (39 research articles) were selected before screening each in full to ultimately select only those studies where the findings presented were specific to the TFCA region or neighbouring areas (seven research articles). Studies describing data collection within or in close proximity to the TFCA region as part of a broader dataset and that didn't present results geographically specific to the TFCA area were removed. This was because findings would add little to the interpretation of spatial outputs.

The second phase of the search identified an additional 50 research articles published between 2020 and 2022, of which eight were rejected at the initial screening because they were not about Malawi or Zambia, because they did not include primary data (e.g. they were review or synthesis papers), and/or they did not identify findings or use data about climate risk, vulnerability and adaptation linked to agriculture. Final screening to identify studies with findings intersecting or bordering the TFCA area of interest identified four research articles.

In total 11 research articles published between 2016 and 2022 were used to consider bivariate mapping outputs for the Malawi-Zambia TFCA region.

Analysis and presentation of results

Methods of analysis: The 11 research articles were analysed to populate an Excel spreadsheet with information about the location of findings and their relevance geographically to the Nyika-North

Luangwa and the Kasungu-Lukusuzi components of the TFCA, the focal agricultural system and climate hazards, and whether the research was vulnerability and/or adaptation oriented. Each paper was read in full and a qualitative summary provided in relation to bivariate mapping outputs.

Information quality: only peer-reviewed data were included in our review in an attempt to assure information quality. More rigorous controls were not possible given time constraints.

Summary of Literature

Of the 11 research articles meeting our criteria, six presented findings relevant to the Nyika-North Luangwa TFCA component and nine to the Kasungu-Lukusuzi component. Four research articles presented findings relevant to both components. The dataset included studies for all years covered in our search. However, and mirroring the trend observed by Quinn et al. (2020) for the broader SADC region, more studies were published in recent years, with nearly three quarters published during or after 2019. The majority of studies centred on arable farming systems, and precipitation hazards were considered more frequently than others, although temperature and drought were often covered too. More or less equal numbers of studies emphasised vulnerability and adaptation.

Tourism Sector

Data source and document selection

As a preliminary exploration of the potential for synthesising literature summarising vulnerability and climate risk to the tourism sector, systematic searches of titles, abstracts and keywords on the SCOPUS and Web of Knowledge databases were conducted on June 10th 2022 for research published between 2016 and 2022 by the same researcher who conducted agricultural focussed searches as outlined in stage 3 above. Search strings were similar to those used for the agricultural sector in stage 3, but modified by replacing ‘agricultur*’ with ‘touris*’ (Table 2). The search produced two potential research articles, one focussed on the Barotse floodplain in Zambia’s Western Province, and the other on the Zambian side of the Victoria Falls. Thus, neither were relevant to the geographic area of this study. This indicates the possibility that research may not have been published recently on this topic area. However, it is recommended more time is given to developing search terms to identify relevant literature for both the tourism and biodiversity sectors so this can be explored thoroughly.

Table 2: Search Strings and Criteria Used to Source Literature for Systematic Review

	Search String	Database Fields	Search Date
Phase 1	(climat*) AND (agricultur*) AND (hazard OR drought OR heat OR hot OR warm* OR temperature OR flood* OR wet OR dry OR rain* OR precipitation OR "sea level rise" OR storm OR "extreme event*" OR salini* OR stress) AND ("Southern African Development Community" OR SADC OR Africa OR Angola OR Botswana OR Comoros OR “Democratic Republic of the Congo” OR DRC OR Eswatini OR Swaziland OR Lesotho OR Madagascar OR Malawi OR Mauritius OR Mozambique OR Namibia OR Seychelles OR “South Africa” OR Tanzania OR Zambia OR Zimbabwe) AND	Web of Science: Topic (Title, abstract, keywords) Scopus: Title, abstract, keywords Dates: 2016-2020	May 5th 2020

	Search String	Database Fields	Search Date
	(vulnerab* OR adapt* OR resilien* OR sensitiv* OR expos* OR risk*)		
Phase 2	(climat*) AND (agricultur*) AND (hazard OR drought OR heat OR hot OR warm* OR temperature OR flood* OR wet OR dry OR rain* OR precipitation OR "sea level rise" OR storm OR "extreme event*" OR salini* OR stress) AND (Malawi OR Zambia OR "Nyika*North Luangwa*" OR "Kasungu*Lukusuzi*") AND (vulnerab* OR adapt* OR resilien* OR sensitiv* OR expos* OR risk*)	Web of Science: Topic (Title, abstract, keywords) Scopus: Title, abstract, keywords Dates: 2020-2022	June 10th 2022
Phase 3	(climat*) AND (agricultur*) AND (hazard OR drought OR heat OR hot OR warm* OR temperature OR flood* OR wet OR dry OR rain* OR precipitation OR "sea level rise" OR storm OR "extreme event*" OR salini* OR stress) AND (Malawi OR Zambia OR "Nyika*North Luangwa*" OR "Kasungu*Lukusuzi*") AND (vulnerab* OR adapt* OR resilien* OR sensitiv* OR expos* OR risk*)	Web of Science: Topic (Title, abstract, keywords) Scopus: Title, abstract, keywords Dates: 2016-2022	June 10th 2022
Tourism sector	(climat*) AND (touris*) AND (hazard OR drought OR heat OR hot OR warm* OR temperature OR flood* OR wet OR dry OR rain* OR precipitation OR "sea level rise" OR storm OR "extreme event*" OR salini* OR stress) AND (Malawi OR Zambia OR "Nyika*North Luangwa*" OR "Kasungu*Lukusuzi*") AND (vulnerab* OR adapt* OR resilien* OR sensitiv* OR expos* OR risk*)	Web of Science: Topic (Title, abstract, keywords) Scopus: Title, abstract, keywords Dates: 2016-2022	June 10th 2022

3.0 Mapping Outcomes

It should once again be noted that all maps and the data depicted within them represent a static snapshot of the Malawi-Zambia TFCA and any interpretation of these maps should be done so relative to the limitations outlined above related to the vulnerability index and to the dynamics of this area only, and not the broader SADC region, African continent or farther afield.

The outcome of mapping the mean quartile of the chosen vulnerability indicators is presented as Figure 3.1. Based on the mapped indicators employed in the vulnerability assessment, there is a distinct difference in average vulnerability across the border region, with the 23km x 23km map cells falling within Malawi being seen to be generally much less vulnerable than those along the Zambian border. Within the TFCA, it is clear that some of the most vulnerable areas are found in the western border area of North Luangwa National Park and the adjoined Musalangu Game Management Area. Based on an analysis of the underlying data for this area, gender inequalities appear to be prominent vulnerabilities, with aspects of poverty and distance to market used to characterize human and physical capital also regularly falling within the lower two quartiles of all figures produced for the mapped area. In contrast to North Luangwa National Park and the Musalangu region, relatively high gender equality scores were found in the Lukusuzi region, which directly raised aggregate vulnerability scores from the lower most vulnerable range of scores (i.e., 1.0 – 2.0) with the National Park.

Conversely, areas of intermediate vulnerability in northern Nyika National Park are characterized by soils that are, relative to the wider area, poor and susceptible to loss[4]. Compared to Luangwa, measures of poverty for the area generally fall within the lower vulnerability ranges (i.e., 2.9 – 3.8) and gender development scores in the higher ranges (i.e., ≥1). Higher average vulnerability scores in northern Lukusuzi National Park appear to be a product of relatively high soil loss in already drought prone areas in addition to being some distance from a market within an urban area possessing a population of 20,000 or more. Given the nature of a national park, i.e. a non-urban protected area, this is perhaps to be expected and should be a point of consideration within any interpretation of the map. Nevertheless, in terms of physical capital and those that live within this area of Lukusuzi National Park, it still presents a source of vulnerability.

[4] It should be noted that the mapped region is, in general, home to good soils in all areas, with regional suitability rarely falling below 5 on the FAO (2007) scale of suitability (with a score of 8 being most suitable).

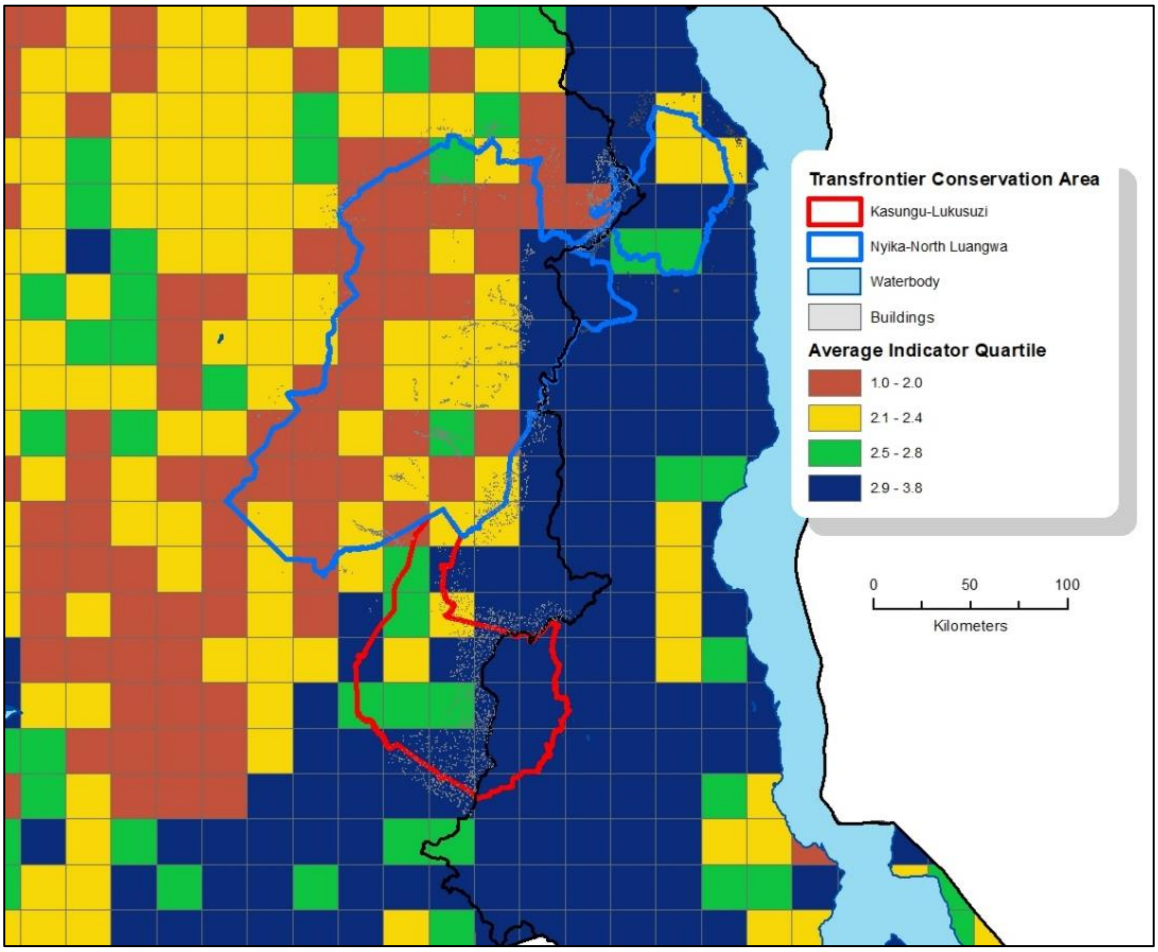

Figure 3.1: Average Vulnerability of Malawi-Zambia TFCA Region (1.0 stands for high vulnerability, 3.8 for low vulnerability)

Figures 3.2 – 3.5 present the mean vulnerability index map for Malawi-Zambia TFCA overlain with map layers for the modelled climate projections for RCP4.5 and RCP8.5[5]. The four maps collectively suggest that by mid-century, rainfall in Kasungu National Park is projected to be relatively high without being extreme in both RCP4.5 and RCP8.5 scenarios (i.e., a mean of 16-17mm/day)[6]. Drought is seen to be present in Kasungu National Park for RCP8.5, and slightly more consistently for RCP4.5, but compared to neighbouring areas the severity of the droughts is relatively low. Comparatively, projections indicate Lukusuzi National Park to be subject to more severe drought in both RCP scenarios across all areas, with pockets of higher rainfall found in the very north and eastern border of the park.

For both RCP scenarios, Nyika is projected to be subject to some of the most extreme rainfall in the mapped area (over 40mm/day in places). Only the extreme north of Nyika National Park demonstrates potential for drought exposure in either RCP scenario. For the Nyika-North Luangwa TFCA sub-component, aside from an isolated pocket of higher rainfall values in the southeast map cell covering Chipondo, Chumanganga and Chirimunganda, and in the adjacent Vwaza Marsh Wildlife Reserve, extreme rainfall is not projected for this wider area. However, drought proves prevalent across North

[5] For reference, future climate projection map layers have been mapped separately for the wider Zambia and Malawi region and are presented within Appendix 1.

[6] The 95th percentile mean daily rainfall for the SADC region is projected to be 12.5mm for RCP4.5 and 12.9mm for RCP8.5.

Luangwa and the adjoined Musalangu Game Management Area for both RCP4.5 and RCP8.5, without being projected to reach the severe status found further west outside of the TFCA (i.e., SPEI = -< -2).

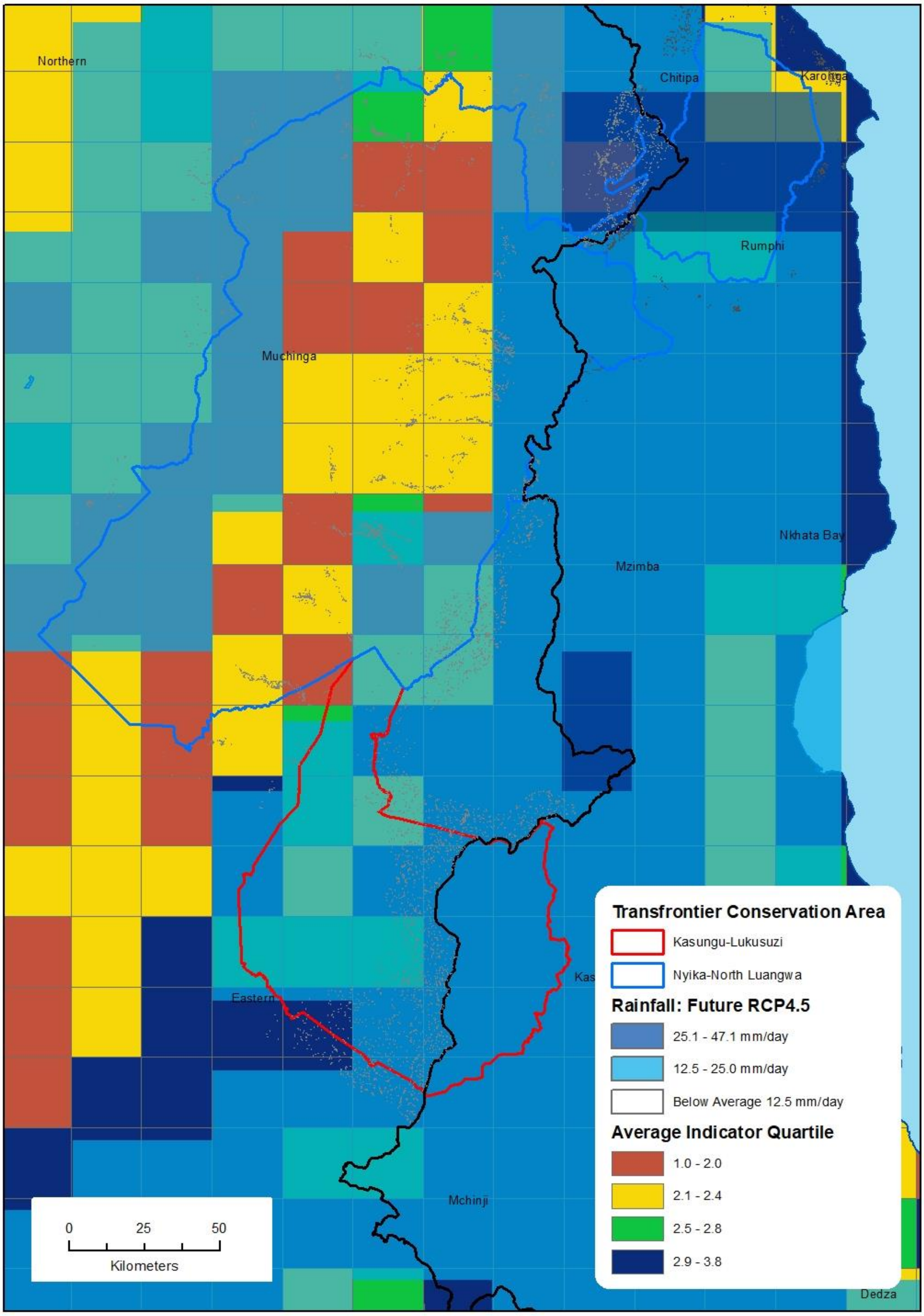

Figure 3.2: 95th Percentile of Rainfall by Mid-Century in RCP4.5 (2031 – 2059)

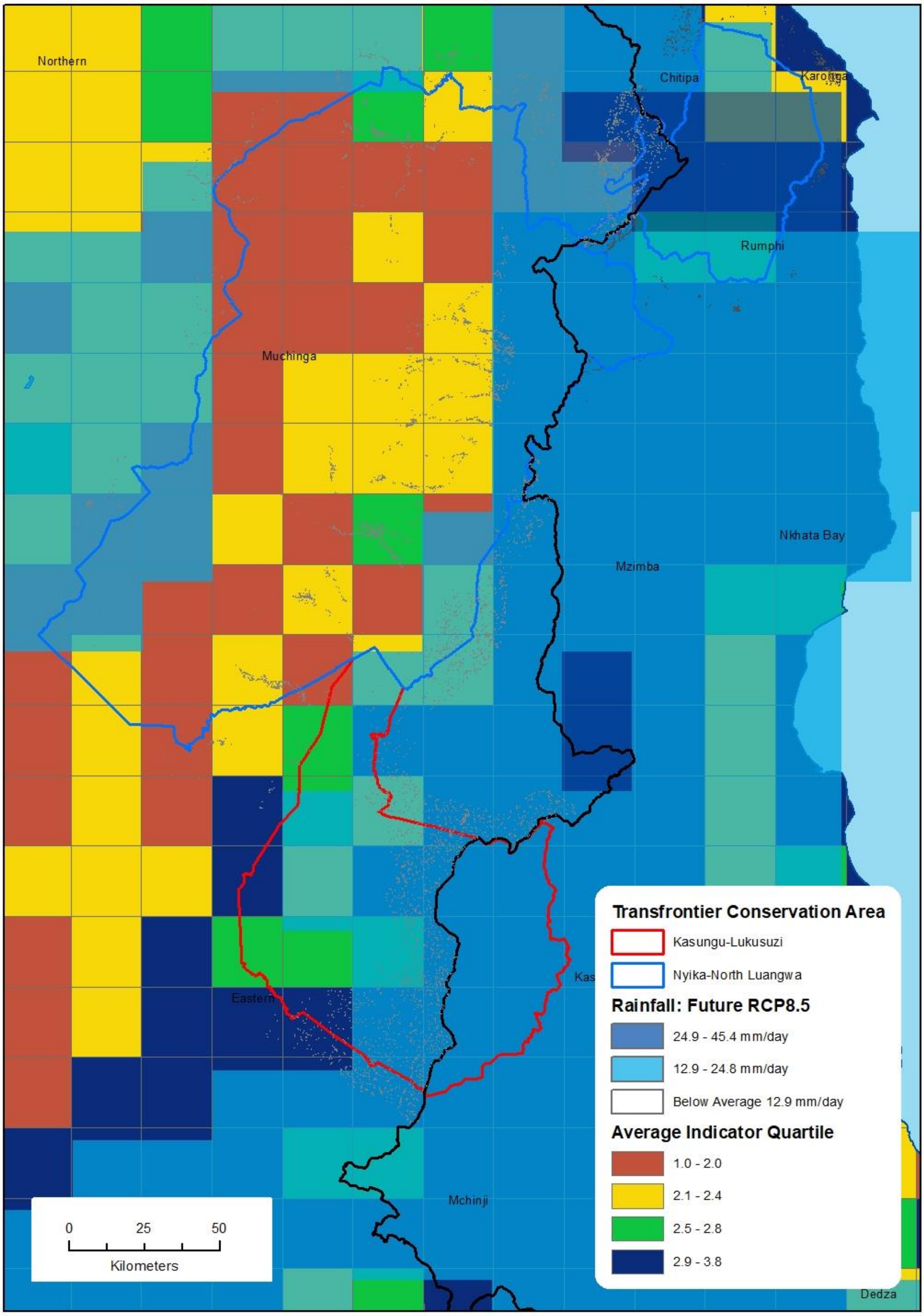

Figure 3.3: 95th Percentile of Rainfall by mid-century in RCP8.5 (2031 – 2059)

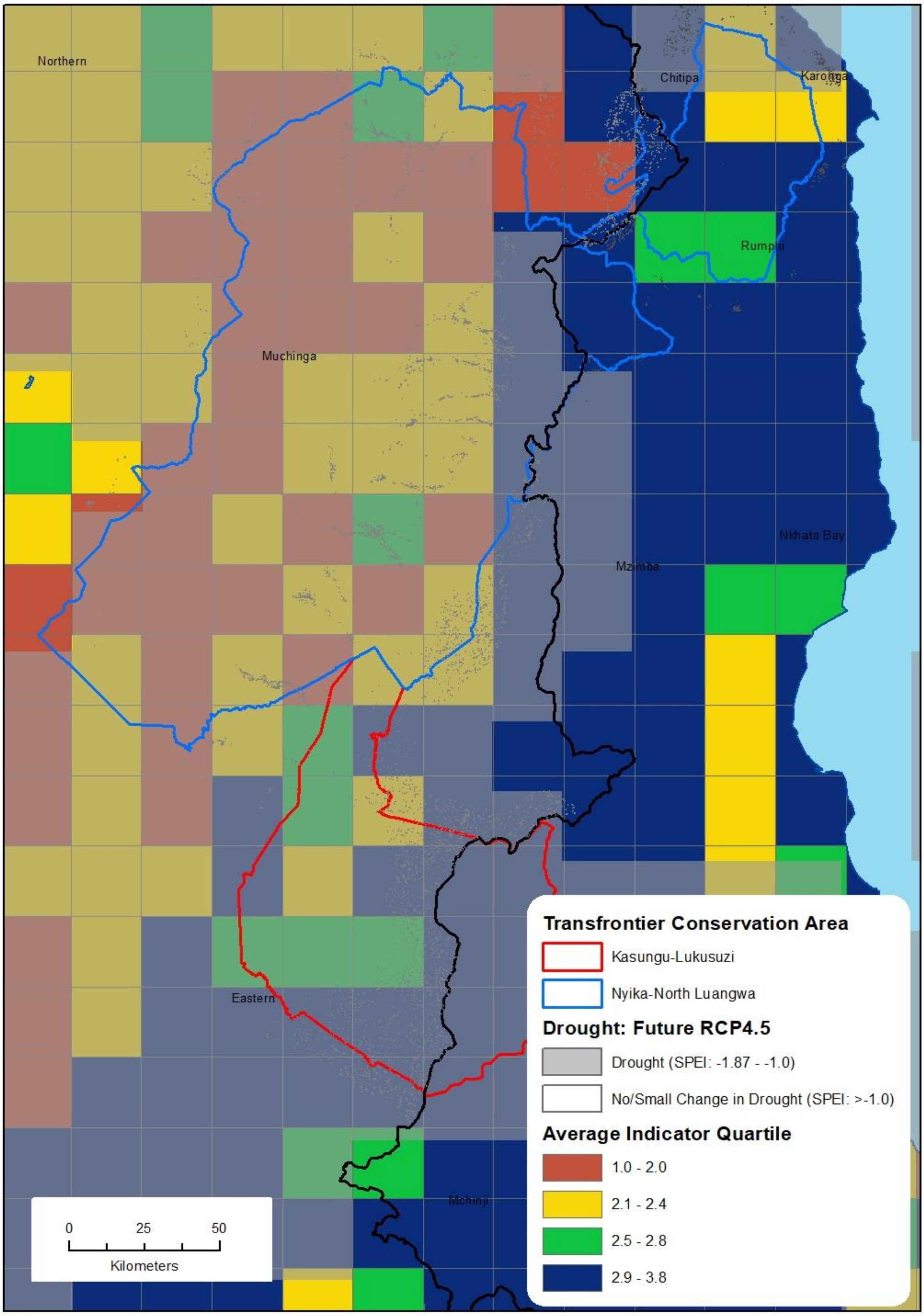

Figure 3.4: Mean 1-Month Mid-century Droughts in RCP4.5 (2031 – 2059)

Note: SPEI <= -1 used to indicated droughts, and SPEI <= -2 indicates severe droughts.

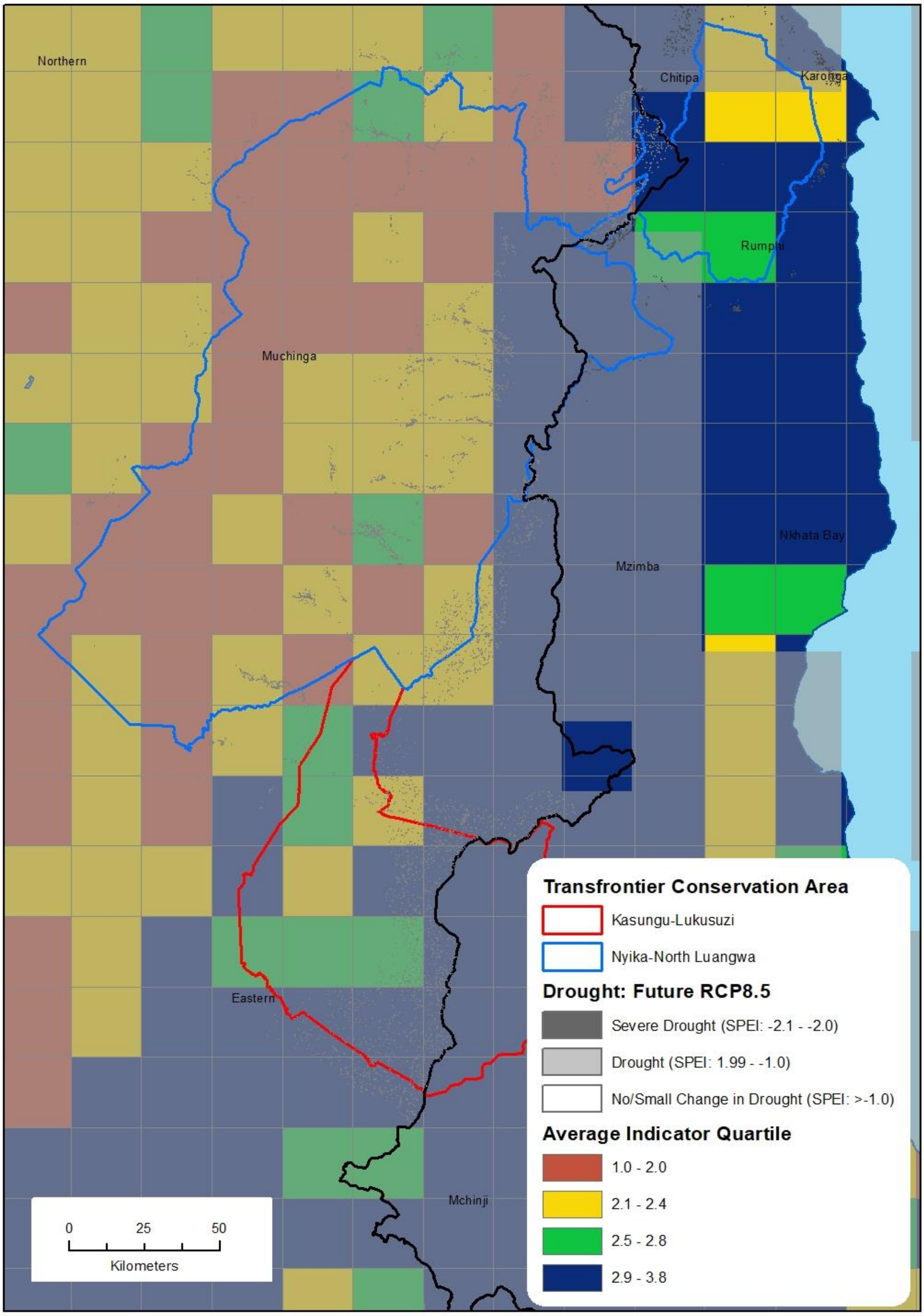

Figure 3.5: Mean 1-Month Mid-century Droughts in RCP8.5 (2031 – 2059)

Note: SPEI <= -1 used to indicated droughts, and SPEI <= -2 indicates severe droughts.

4.0 Hotspot Analysis

4.1 Climate Risk Hotspots

To identify hotspots of climate risk, bivariate choropleth maps were produced as they facilitate the clear identification of areas that intersect extreme hazard risk and high vulnerability. Vulnerability is represented from high (reds), medium high (oranges), medium low (dark greens) and low (blues), while climate hazards are represented by colour shading for high (darker reds), medium-high (darker oranges) to medium low (lighter greens) and low (lighter blues). For quick reference, colours at each corner of a bivariate map legend provide direction to areas of greatest interest and, in this case, extreme high climate *risk* (dark red) and extreme low climate *risk* (dark blue). Within the bivariate legend the normalised and rounded mean score for both vulnerability and climate hazards are also provided. The first digit of the two-digit number represents the mean vulnerability score, and the second represents the mean climate risk score (e.g., the number 34 on the legend equates to 'medium low vulnerability', 'low climate risk').

Bivariate maps for the Malawi-Zambia TFCA are presented below (Fig: 4.1 – 4.4) and followed by bivariate maps for the Kasungu-Lukusuzi TFCA sub-component (Fig: 4.5 - 4.8)[7], which are overlain with a buildings map layer depicting populated areas in and within 10km of the TFCA boundary. Interpreting the integration of vulnerability and climate hazards into the bivariate maps, other than a small reduction in climate risk in northern Lukusuzi National Park, from medium high vulnerability - high climate hazard in RCP4.5, to medium high vulnerability and climate hazard in RCP8.5, there is little change in overall climate risk between future rainfall climate scenarios. Across both scenarios, there are no high vulnerability – high climate hazard map cells displayed for future rainfall. However, rainfall is deemed a high hazard throughout Kasungu National Park and map cells depicting medium high vulnerability – high climate hazard are prevalent to the west of Luangwa National Park and the adjoined Musalangu Game Management Area, within the transition zone to Nyika National Park and within northern Nyika National Park itself.

For drought, medium high vulnerability - high climate hazard is seen through most of Luangwa and the adjoining Game Management Area to the north, with northern Lukusuzi National Park also possessing areas of medium high vulnerability – high climate hazard (and widespread medium low vulnerability - high drought hazard). Climate risk in the Musalangu Game Management Area of the Luangwa district marginally reduces in the far north, to medium high vulnerability – medium high climate hazard for the RCP8.5 scenario. Notably, however, it is clear that significant areas of medium high vulnerability – high climate hazard are projected for both RCP4.5 (i.e., a global climate action scenario) and RCP8.5 (i.e., a scenario reflecting no current or future climate action). Based on the mapping outcomes, Section 4.2 provides further discussion of the TFCA region's 'hottest' spots complemented by a literature review of all relevant Malawi-Zambia TFCA climate risk literature identified as described in Section 2.4.

[7] For reference, and comparison to figures 4.1 - 4.8, bivariate maps for the wider Zambia and Malawi region are presented within Appendix 2.

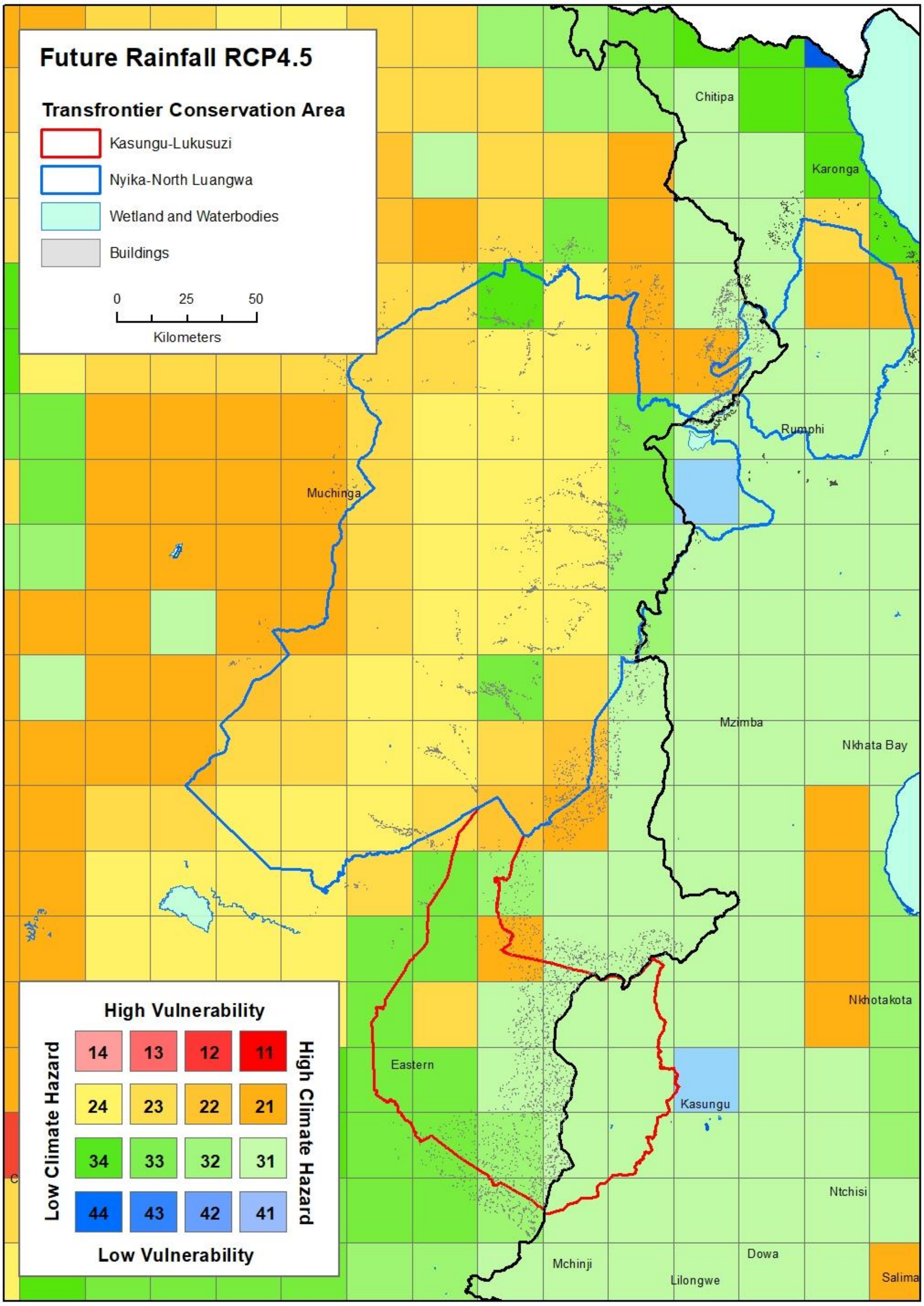

Figure 4.1 Malawi-Zambia TFCA Bivariate Future Rainfall Vulnerability Map (RCP4.5) (the first digit of the two-digit number represents the mean vulnerability score, and the second represents the mean climate risk score (e.g., the number 34 on the legend equates to 'medium low vulnerability', 'low climate risk')

(Source data: TFCA Boundary: Peace Parks Foundation Open Data; Buildings, Wetlands and Waterbodies: © OpenStreetMap, available under the Open Database Licence)

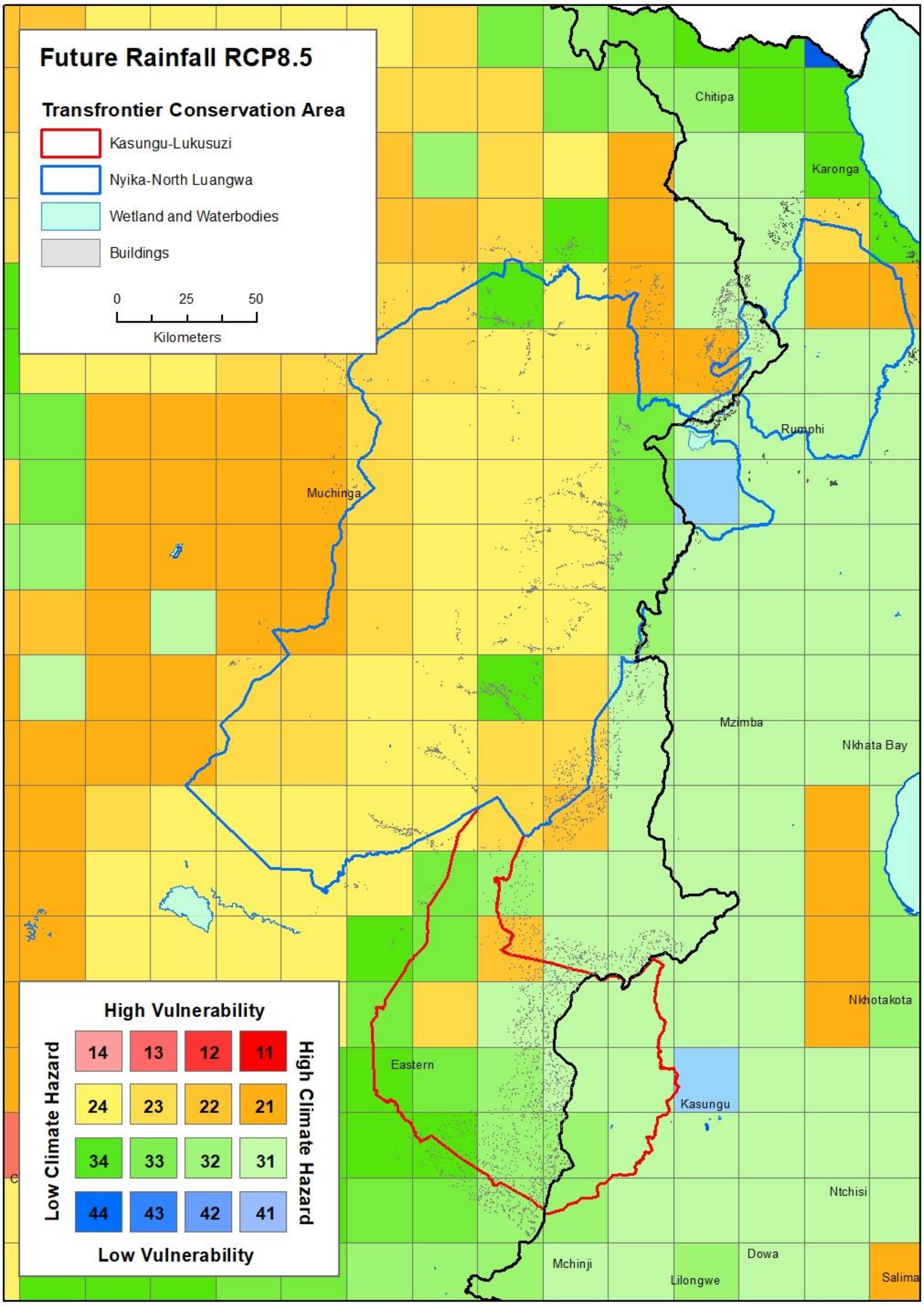

Figure 4.2: Malawi-Zambia TFCA Bivariate Future Rainfall Vulnerability Map (RCP8.5) (the first digit of the two-digit number represents the mean vulnerability score, and the second represents the mean climate risk score (e.g., the number 34 on the legend equates to 'medium low vulnerability', 'low climate risk')

(Source data: TFCA Boundary: Peace Parks Foundation Open Data; Buildings, Wetlands and Waterbodies: © OpenStreetMap, available under the Open Database Licence)

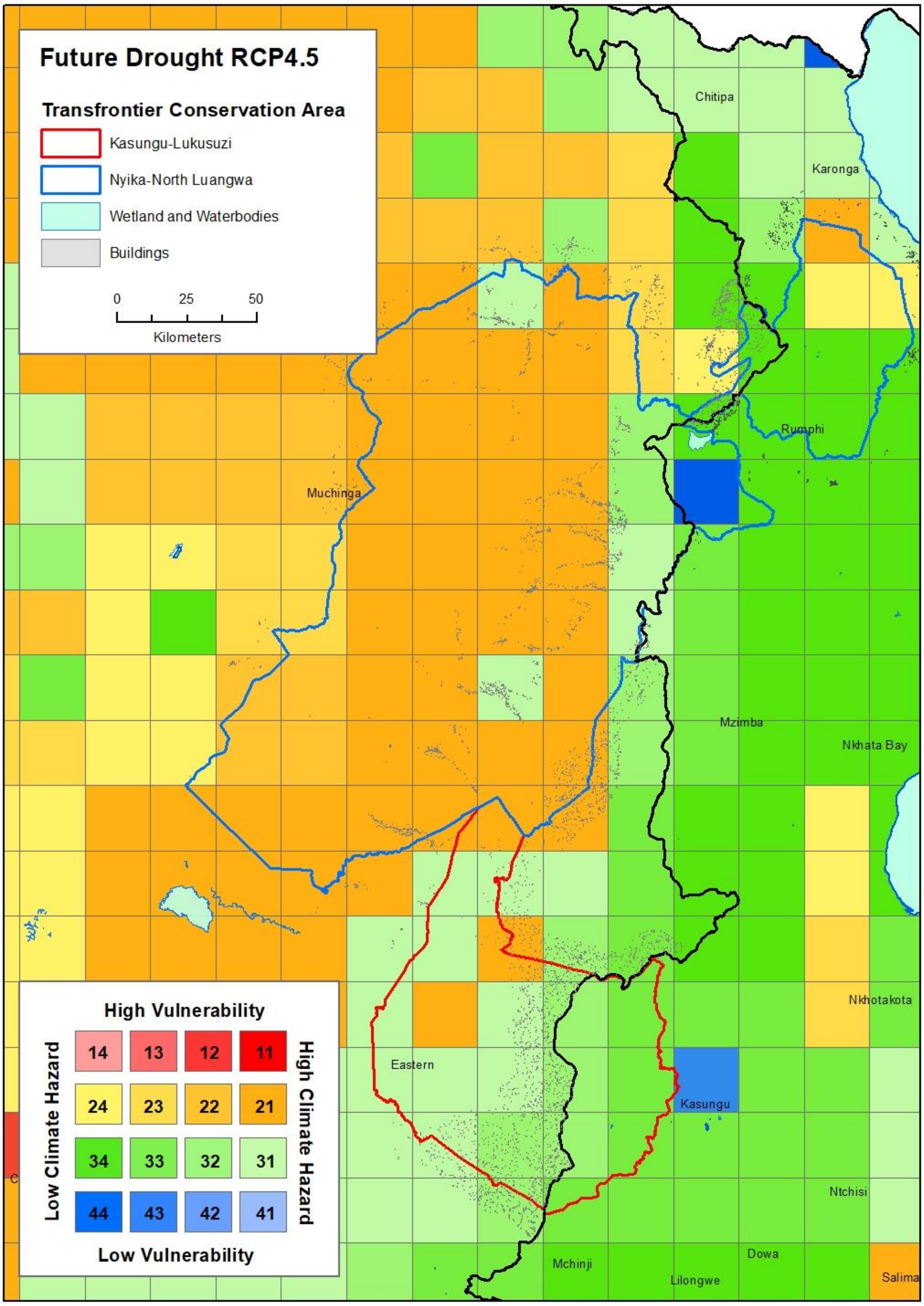

Figure 4.3: Malawi-Zambia TFCA Bivariate Future Drought Vulnerability Map (RCP4.5) (the first digit of the two-digit number represents the mean vulnerability score, and the second represents the mean climate risk score (e.g., the number 34 on the legend equates to 'medium low vulnerability', 'low climate risk')

(Source data: TFCA Boundary: Peace Parks Foundation Open Data; Buildings, Wetlands and Waterbodies: © OpenStreetMap, available under the Open Database Licence)

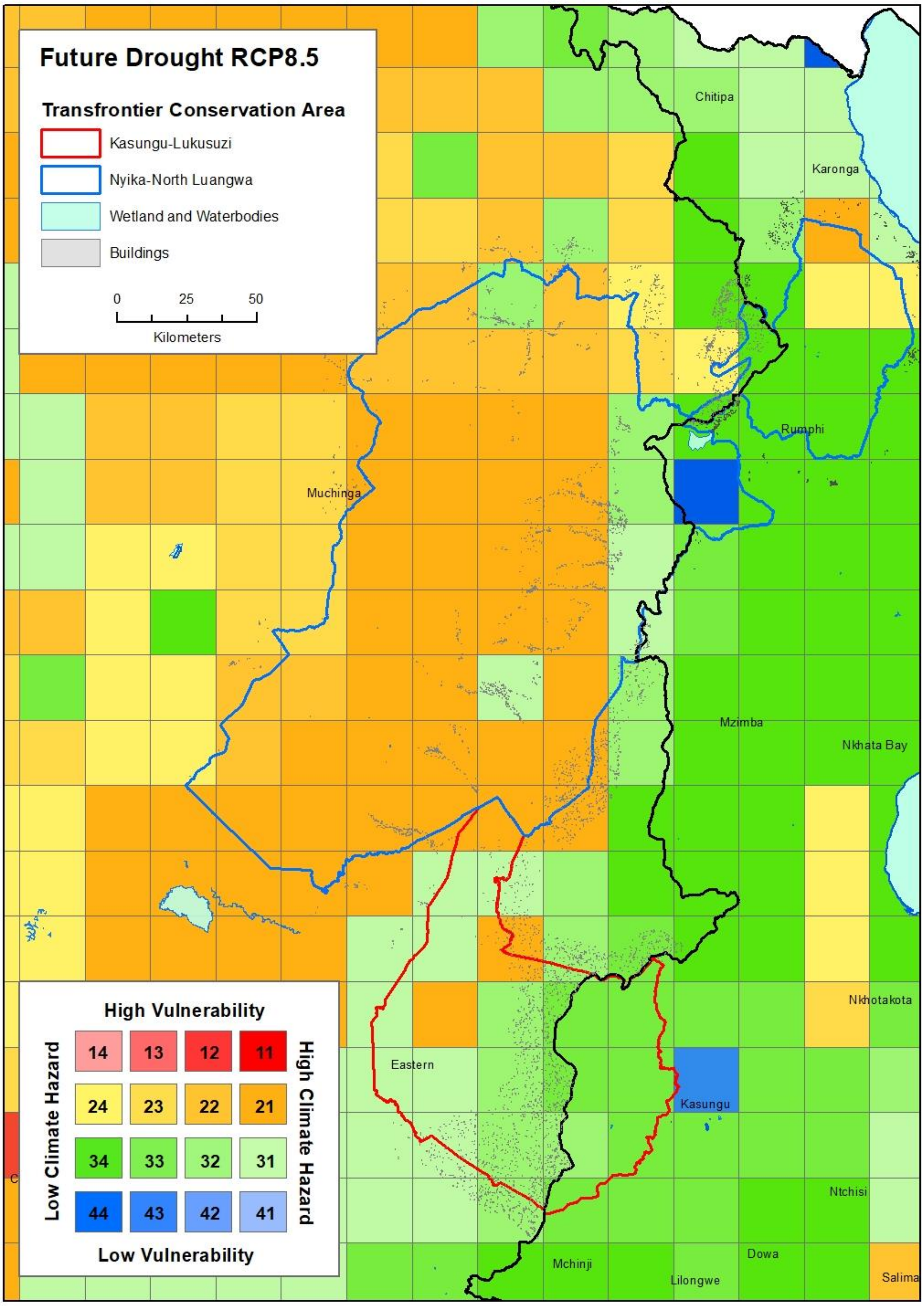

Figure 4.4: Malawi-Zambia TFCA Bivariate Future Drought Vulnerability Map (RCP8.5) (the first digit of the two-digit number represents the mean vulnerability score, and the second represents the mean climate risk score (e.g., the number 34 on the legend equates to 'medium low vulnerability', 'low climate risk')

(Source data: TFCA Boundary: Peace Parks Foundation Open Data; Buildings, Wetlands and Waterbodies: © OpenStreetMap, available under the Open Database Licence)

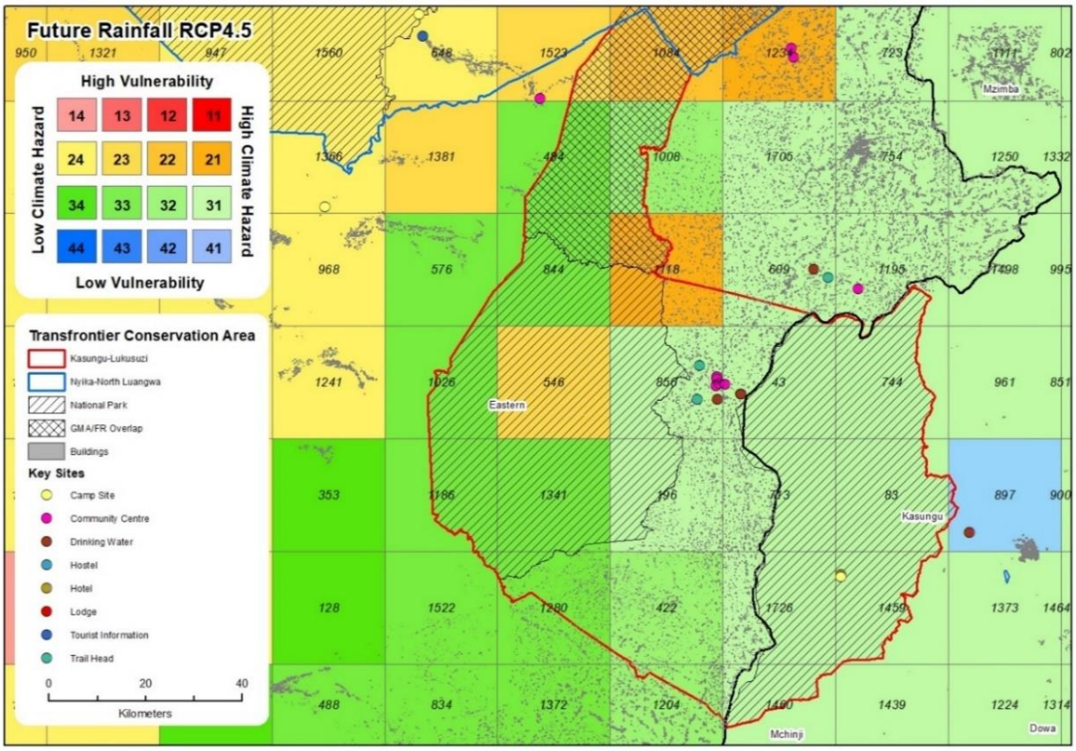

Figure 4.5: Kasungu-Lukusuzi Bivariate Future Rainfall Vulnerability Map (RCP4.5) (the first digit of the two-digit number represents the mean vulnerability score, and the second represents the mean climate risk score (e.g., the number 34 on the legend equates to 'medium low vulnerability', 'low climate risk')

(Source data: TFCA Boundary: Peace Parks Foundation Open Data; Buildings, Wetlands and Waterbodies, Key Sites: © OpenStreetMap, available under the Open Database Licence)

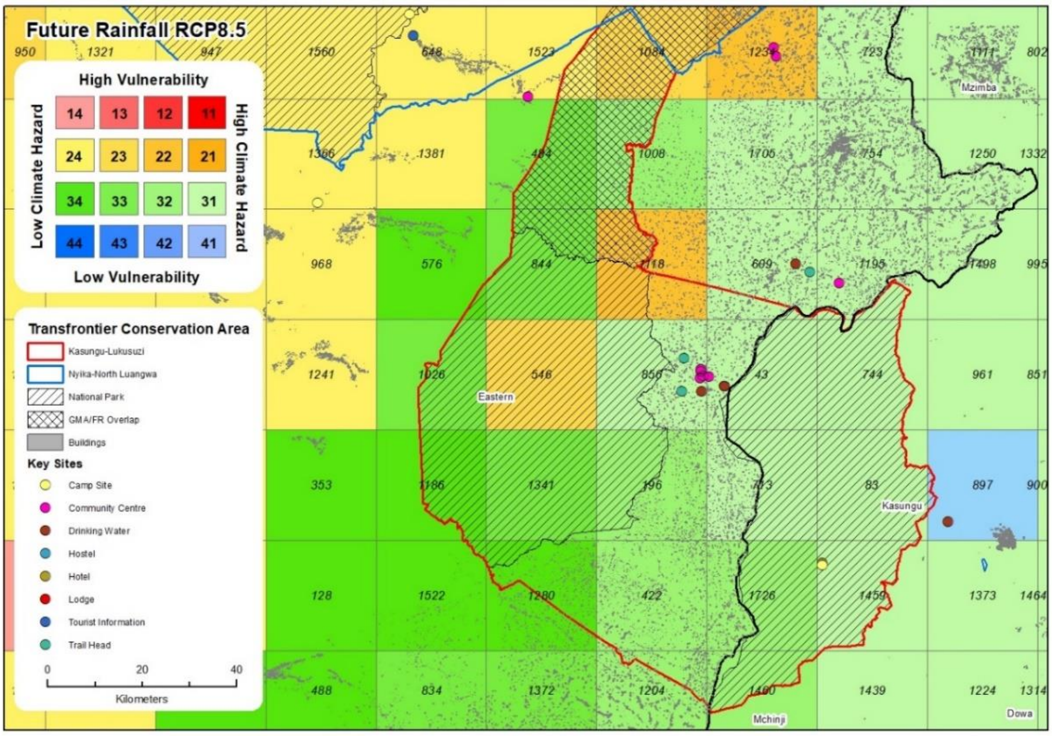

Figure 4.6: Kasungu-Lukusuzi Bivariate Future Rainfall Vulnerability Map (RCP8.5)

(Source data: TFCA Boundary: Peace Parks Foundation Open Data; Buildings, Wetlands and Waterbodies, Key Sites: © OpenStreetMap, available under the Open Database Licence)

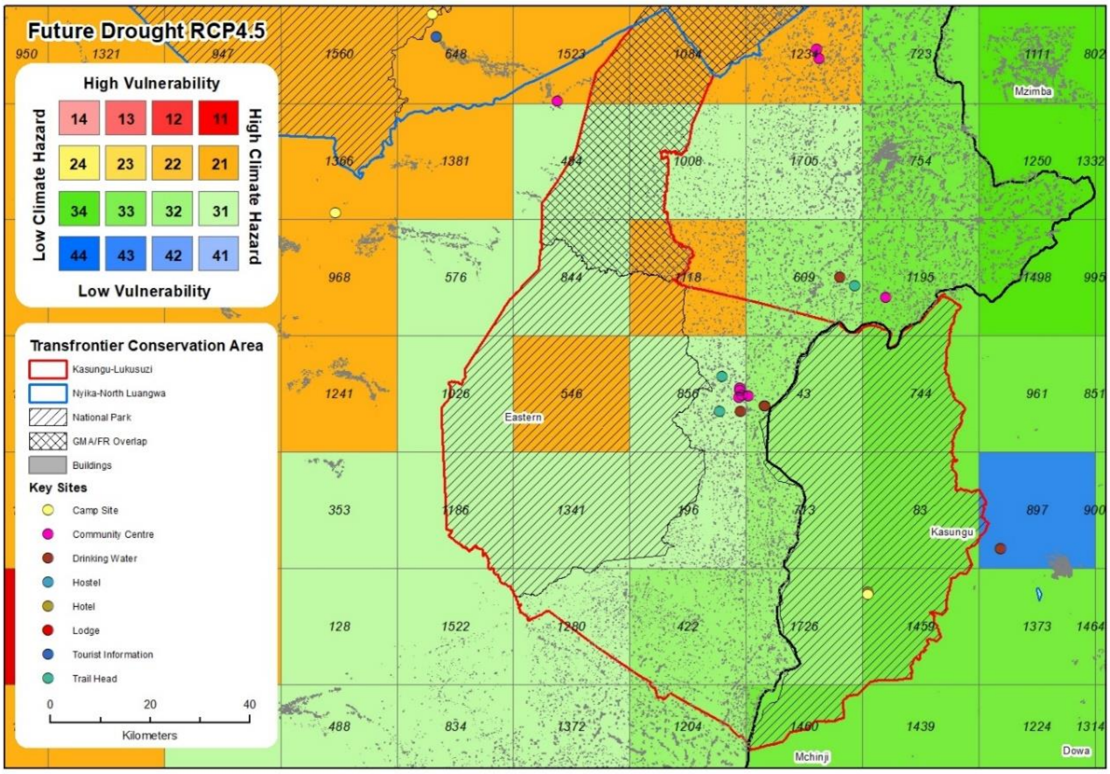

Figure 4.7: Kasungu-Lukusuzi Bivariate Future Drought Vulnerability Map (RCP4.5)

(Source data: TFCA Boundary: Peace Parks Foundation Open Data; Buildings, Wetlands and Waterbodies, Key Sites: © OpenStreetMap, available under the Open Database Licence)

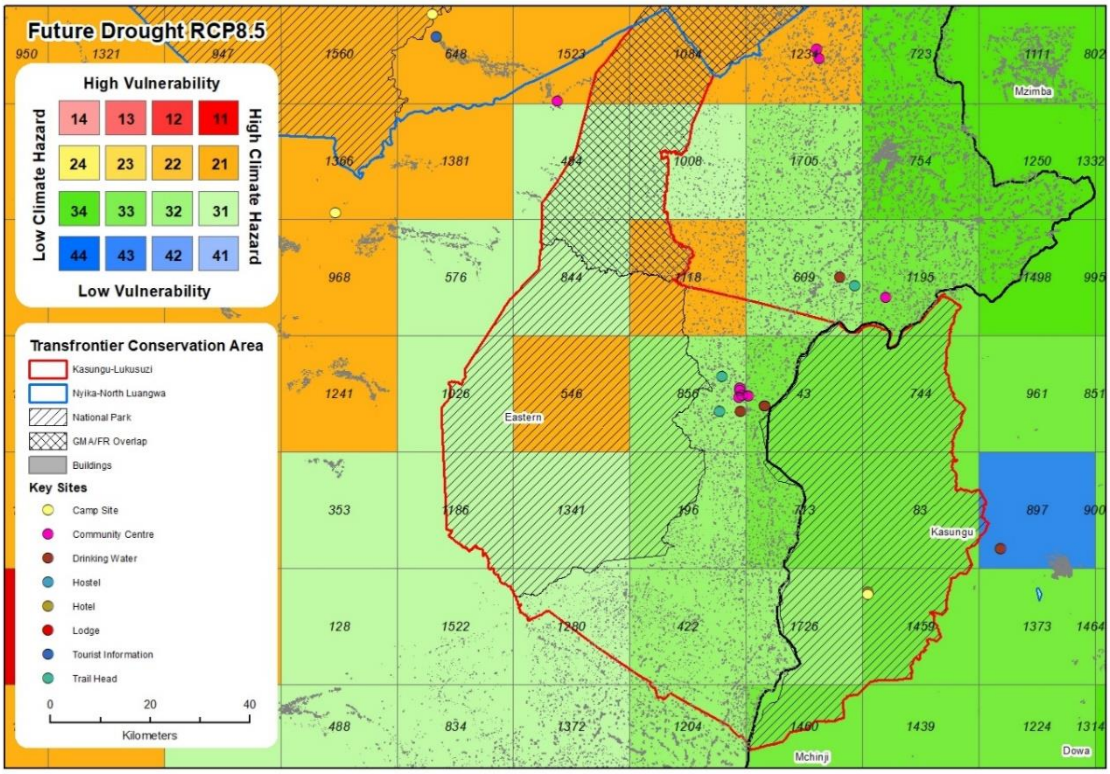

Figure 4.8: Kasungu-Lukusuzi Bivariate Future Drought Vulnerability Map (RCP8.5)

(Source data: TFCA Boundary: Peace Parks Foundation Open Data; Buildings, Wetlands and Waterbodies, Key Sites: © OpenStreetMap, available under the Open Database Licence)

4.2 Literature Review

In a departure to the approach of Quinn et al (2020) who used outputs from the systematic literature review to focus their synthesis of the state of knowledge on hotspots of climate risk and vulnerability, this synthesis is focussed more broadly on the TFCA region. This is because the scale of analysis meant most literature would have been excluded with a singular focus on the hottest spots within the TFCA as shown on Figures 4.1 - 4.8. In our synthesis, we draw attention to hot areas where they overlap with research findings. The following synthesis is structured loosely around the two TFCA sub-components.

Kasungu-Lukusuzi

None of the studies meeting our search criteria focussed specifically on the areas identified as medium-high vulnerability and climate hazard towards the north of Lukusuzi National Park on the Zambia side of the Kasungu-Lukusuzi TFCA. However, seven studies were conducted with findings presented within or proximal to these areas and the remaining Kasungu-Lukusuzi TFCA boundary. With the exception of the two higher risk areas mentioned above, vulnerability was medium across the region, future drought hazard low on the Malawian side and high on the Zambian side, and future rainfall hazard low on the Zambian side and high on the Malawian side. Four studies were located on the Malawian side, three on the Zambian side and one covered the entire area. These studies explored climatic impacts on crops and optimized crop planting based on historic and projected climate conditions, the adoption of climate smart agriculture and agroecology, and local knowledge about climate impacts and adaptations. Equality aspects linked to the latter two topics, particularly gender, were considered in six studies.

Research exploring potential crop impacts under RCP4.5 and RCP8.5 emission scenarios resulted in recommendations for optimised planting linked to climate suitability to support agricultural productivity in both Zambia and Malawi. Based on assessed risk of maize crop failure in the near (2035-2066) and far (2065-2096) future across Zambia related to dry spells, heat stress, and precipitation induced flooding or waterlogging, Siatwiinda et al. (2021) concluded that optimised planting dates and maize varieties could have positive impacts on maize yields. In and around the Kasungu-Lukusuzi TFCA, including areas identified as medium to high vulnerability and climate hazard risk, the use of late maturing maize varieties and planting dates between 27th November and 17th December were recommended, alongside improved nutrient management to boost maize production. In Malawi, Zuza et al. (2021) identify macadamia as one of the most important and profitable crops, and one for which areas of climatic suitability were estimated to reduce by between 18% and 22% by the 2050s. The nation-wide study indicated much of the Kasungu National Park and eastern bordering areas to be optimal for macadamia production under current conditions.

Suitability for macadamia along the southern border of the Kasungu National Park was more marginal, and these areas were considered vulnerable under RCP4.5 emissions scenarios. Under RCP8.5 scenarios, vulnerability was estimated to extend further north into currently optimal areas. Zuza et al. (2021) encouraged the use of improved varieties, agroforestry, and intercropping, and recommended that farmers adopt moisture conservation measures and develop irrigation infrastructure to meet the water requirements for macadamia growth, particularly during the hotter and drier months of the year. Working in the Kasungu Agricultural Development Division, and underpinned by agricultural, meteorological and hydrological indices calculated from historic data that identified unpredictable rainfall patterns and frequent mild to moderate droughts which were more severe in the Kasungu District relative to Districts studied further south and east, Chikabvumbwa et al. (2022) recommended the promotion of crops that can withstand water stress (e.g. cassava and groundnuts), alongside drought adaptations, such as rainwater harvesting and drip irrigation technologies.

Factors influencing the adoption of climate smart agriculture (CSA) technologies or agroecological practices were the focus of four studies covering Kasungu, Lundazi, Mambwe and Chipata Districts (Bezner Kerr et al., 2019; Murray et al., 2016; Mutenje et al., 2019; Umar, 2021), where our spatial outputs generally identify areas of low-medium vulnerability currently but medium-high future rainfall risk (Kasungu and Lundazi Districts) and medium-high drought risk (Lundazi and Chipata Districts). Overall, all concluded that conservation agriculture technologies had potential for smallholders as adaptations within climate smart agricultural systems. Mutenje et al., (2019) identified that CSA options combining soil and water conservation management practices, improved maize varieties, and cereal-legume diversification were economically viable and worthy of implementation by smallholder farmers, but cautioned that optimal approaches will include a range of options that meet spatial and temporal conditions, rather than a 'one-size fits all' approach.

All CSA studies highlighted gendered aspects of adoption and thus the problematic nature of gender-neutral strategies for encouraging and enabling CSA uptake. In combination, Murray et al. (2016) and Umar (2021) note that women's access to agricultural tools, manure, transport and rural energy raises challenges, and highlight issues linked to labour demands. Based on their observations of increased investments in interventions in households actively headed by women, Mutenje et al. (2019) suggest that better understanding intra-household decision-making dynamics when developing interventions is important to uptake, and that including strategies that improve the equity of decision-making may strengthen ability to select suitable CSA options and build climate resilience. Turning to the potential for adoption of agroecological practices, Bezner Kerr et al. (2019) showed that participation in an action research project supporting experimentation by smallholders increased legume diversification, intercropping and use of compost, manure and crop residues. It also increased food security and dietary diversity, particularly in households where farming knowledge was shared among spouses.

Studies exploring local knowledge about climate impacts and adaptations, and knowledge dynamics, were undertaken in villages where vulnerability is currently low-medium in proximity to the south-western border of the Kasungu-Lukusuzi TFCA on the Zambian side where future rainfall hazard risk was moderate and drought hazard risk high (Mulenga et al., 2017), and to the east of Kasungu National Park on the Malawi side where future drought hazard risk was low, but rainfall hazard risk high (Bezner Kerr et al., 2019, 2018). In both locations, participants described changes in climate that included a shortening of the rainy season, an increase in intra-seasonal rainfall variation, and more localised rainfall patterns (Bezner Kerr et al., 2018; Mulenga et al., 2017). Mulenga et al. (2017) draw attention to inconsistency between local accounts and meteorological data to highlight the value of the different knowledge sources and their complementarity, and conclude by cautioning against reliance on single information sources in the development of climate change-related strategies. Bezner Kerr et al. (2018) describe how action research that encouraged experimentation with agroecological farming methods elevated participant perceptions of their own observations and informal farmer networks as knowledge sources, despite previous emphasis placed on formal extension advice. Importantly, the study also revealed agricultural knowledge and knowledge flow dynamics to be shaped by gender and other social inequalities, with clear implications for the development of adaptation strategies.

Nyika-North Luangwa

Almost the entire North Luangwa section of the Nyika-North Luangwa TFCA component achieved medium-high bivariate vulnerability and future drought risk hazard scores. However, only one study meeting our search criteria presented agricultural climate change risk, vulnerability and/or adaptation findings specific to this location. Given the close proximity of North Luangwa to the Kasungu-Lukusuzi TFCA component, the findings of Siatwiinda et al. (2021) for optimizing wheat yields under RCP4.5 and RCP8.5 scenarios are the same as described above.

Five studies conducted research with findings proximal to the Malawian side of the Nyika-North Luangwa TFCA component, where northern parts of the Nyika National Park achieved a medium-high bivariate vulnerability and future drought risk hazard score, and high scores for vulnerability and future rainfall risk. Two were previously introduced. In line with the overall trend identified by Zuza et al. (2021) for macadamia production to shift northwards by the 2050s, currently suitable areas within and around the North Luangwa-Nyika component of the TFCA were considered likely to remain suitable under both emissions scenarios. With a second study site in Mzimba District located to the south of Nyika National Park and east of Vwaza Wildlife Reserve, the findings of Bezner Kerr et al. (2019, 2018) presented above about agroecology and knowledge dynamics are also relevant to the Malawian side of the Nyika-North Luangwa TFCA component.

Linking to the research described previously by Mulenga et al. (2017) in Central Malawi, Haghtalab et al. (2019) analyse CHIRP, CHIRPS, ARC2, and PERSIANN-CDR gridded rainfall products for a period covering 1981- 2018 at fine resolution to look for evidence of rainfall patterns reported anecdotally by farmers, but not necessarily supported by other knowledge sources. Statistically significant changes in rainy season dynamics were observed for roughly one-third of Malawi, and while no significant change was evident for any single variable for much of the country, persistent change was apparent in some areas including that covered by and proximal to Nyika National Park and Vwaza Wildlife Reserve. These areas showed high variability and dramatic localized shifts including around two fewer days per decade with extreme events, an end of season around five days per decade earlier, and around five fewer dry days per decade over the studied period. The authors emphasise that different trends were evident in the different rainfall products, and recommended further verification.

Finally, Kamanga et al. (2020) conducted a flood and drought vulnerability assessment in Karonga District which may provide further insight about the areas identified in our analysis as being of both medium-high vulnerability and future climate hazard risk. A range of exposure, susceptibility and capacity indicators informed by the community-based disaster risk index and relevant literature were used. They were measured based on expert opinions from local representatives and secondary social and spatial data, to indicate the area to be of moderate to high vulnerability with low exposure due to rurality, high susceptibility linked to environmental and socio-economic factors related particularly to low income, and moderate capacity to respond to droughts and floods, which the authors indicate is likely lower in reality.

5. Summary and Recommendations

The rapid risk assessment of the Malawi-Zambia TFCA, incorporating the North Luangwa, Nyika, Lukusuzi and Kasungu national parks and adjoining game management areas, highlighted several areas potentially at heightened risk of future climate impacts. Though no extreme hotspots were identified within the focus study area, areas of medium high vulnerability – high climate hazard were observed for rainfall in the far north of Lukusuzi National Park and Nyika National Park, with drought projections highlighting areas of medium high vulnerability – high climate risk in North Luangwa and the Musalangu Game Management Area to the north. Generally, the maps suggest that vulnerability is greater in Zambia than in Malawi, with drought and rainfall hazards being more prevalent in Zambia and Malawi, respectively. Compared to Malawi, marginally greater gender inequalities appear to be a key determinant of the heightened mean vulnerability scores observed in Zambia, particularly in the Luangwa region. However, multidimensional poverty was more pronounced across Malawi, and particularly within the area covered by the Nyika National Park. These findings present areas for potential further investigation.

Concluding this report, it should be noted that the methods used to develop the vulnerability index and bivariate climate risk maps remain experimental, with minimal sensitivity analysis conducted in terms of exploring the relative influence of some methodological decisions. For example, no weighting of vulnerability indicators was employed in either this or the original SADC region risk mapping exercise, which depending on the specific aim and context of the study, could prove useful in the decisive identification of climate risk hotspots. Notwithstanding the experimental nature of some elements of this research, the greatly improved resolution of the study in terms of mapping scale and data sampling methods has produced maps that provide a more robust spatial representation of potential climate risk. The improved resolution of the maps also facilitated a more targeted review of research relevant to the region and locations identified to be at heightened climate risk. As such, it is recommended that the results of this study should be used to provide a starting point for engagement with local Malawi-Zambia TFCA stakeholders prior to the development of climate sensitive management plans for the area.

Engagement and follow-on project development activities should include:

- *A 'ground truthing' exercise*: as part of any participatory activities, and before any climate plans are developed and actioned, it is recommended that the findings of the vulnerability mapping exercise undergo some degree of 'ground truthing' via direct in-the-field observation and discussion with local communities and leaders of key economic sectors in the region. This exercise should be used to gather and apply contextual nuance to the higher level results provided by the climate risk maps and complementary literature review.

- *Appraisal of local agricultural activities*: given the focus on rural livelihoods of this study, a clear understanding of land tenure and specific agricultural activities, including confirming the share and scale of smallholder and larger commercial activities in areas deemed to be climate risk hotspots, is required to more broadly determine the potential impact of future extreme climate events in these areas.

- *Appraisal of local governance and financial variations*: due to not being able to identify and include a suitable governance indicator in the vulnerability index (that could be geographically mapped), developing an understanding of local governance influences on the formation and implementation of climate smart management plans is essential. Likewise, the omission of agricultural and per capita GDP from the vulnerability index, without being replaced by alternative subnational indicators of financial capital, means that some understanding of this key potential vulnerability must be obtained prior to any climate risk management planning.

- *Development of a tourism vulnerability index*: though it was not possible within this study to incorporate an element of tourism livelihood vulnerability into the risk mapping exercise, such an activity would be of significant interest and value to local stakeholders in the development of integrated climate action plans. With the potential to both impact and be impacted upon by existing and future regional agricultural activities, tourism (including the land and biodiversity it relies on) is an obvious sector of interest within the study area. Subject to the identification of suitable data and/or the resources required to produce robust primary data, a dedicated livelihood vulnerability index covering tourism should be produced for use in future climate risk mapping. The results of such work should be compared and contrasted to the findings of this report.

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Appendix 1: Regional Climate Projection Maps

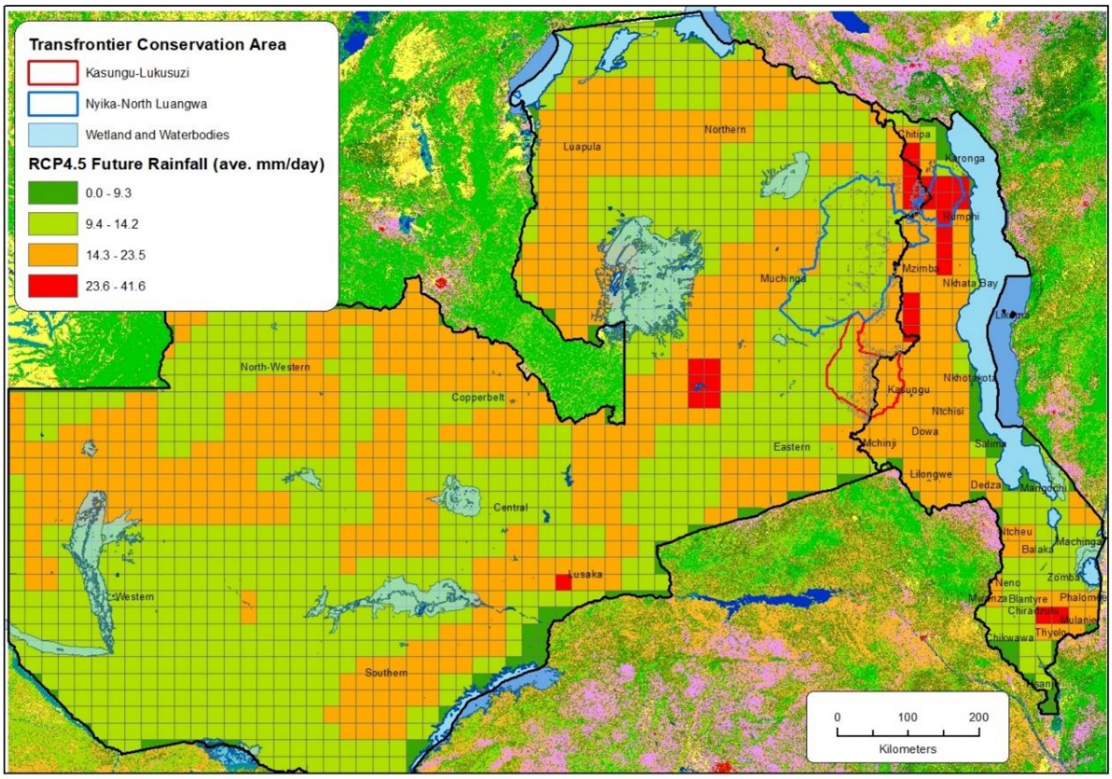

Figure A.1.1: Map of Regional Future Rainfall (RCP4.5)

(Data sources: National Boundaries: GADM V4.1; Land Cover: © Copernicus Service Information 2019)

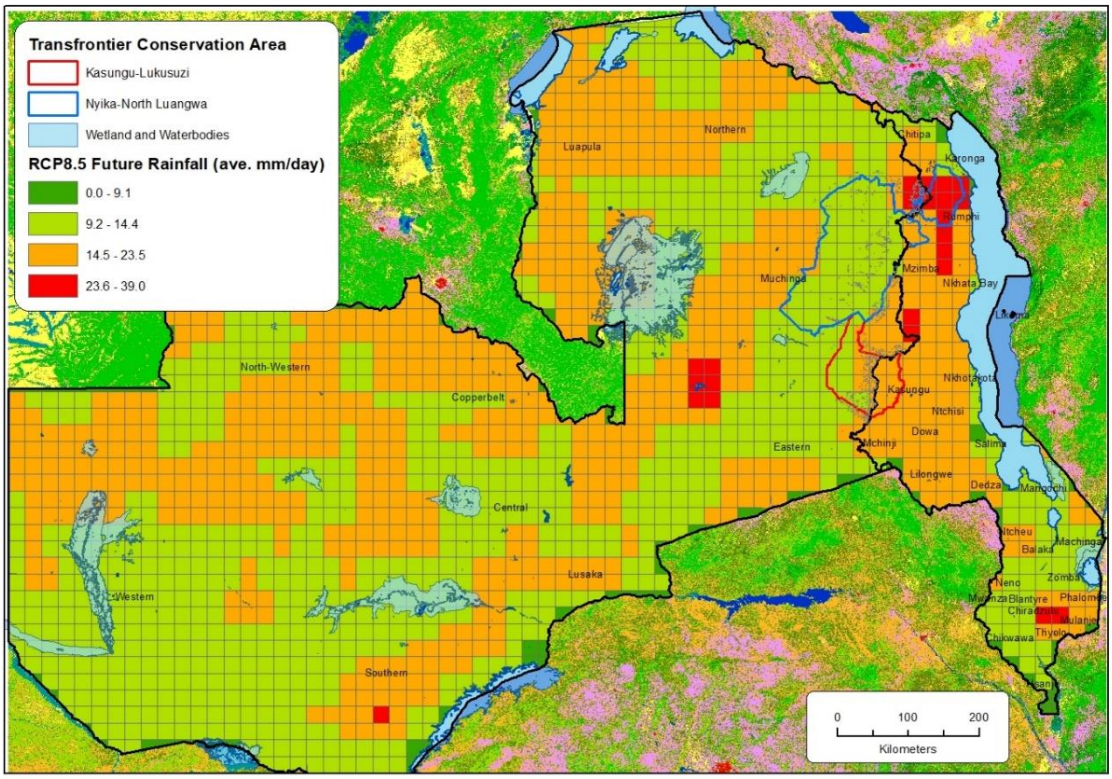

Figure A.1.2: Map of Regional Future Rainfall (RCP8.5)

(Data sources: National Boundaries: GADM V4.1; Land Cover: © Copernicus Service Information 2019)

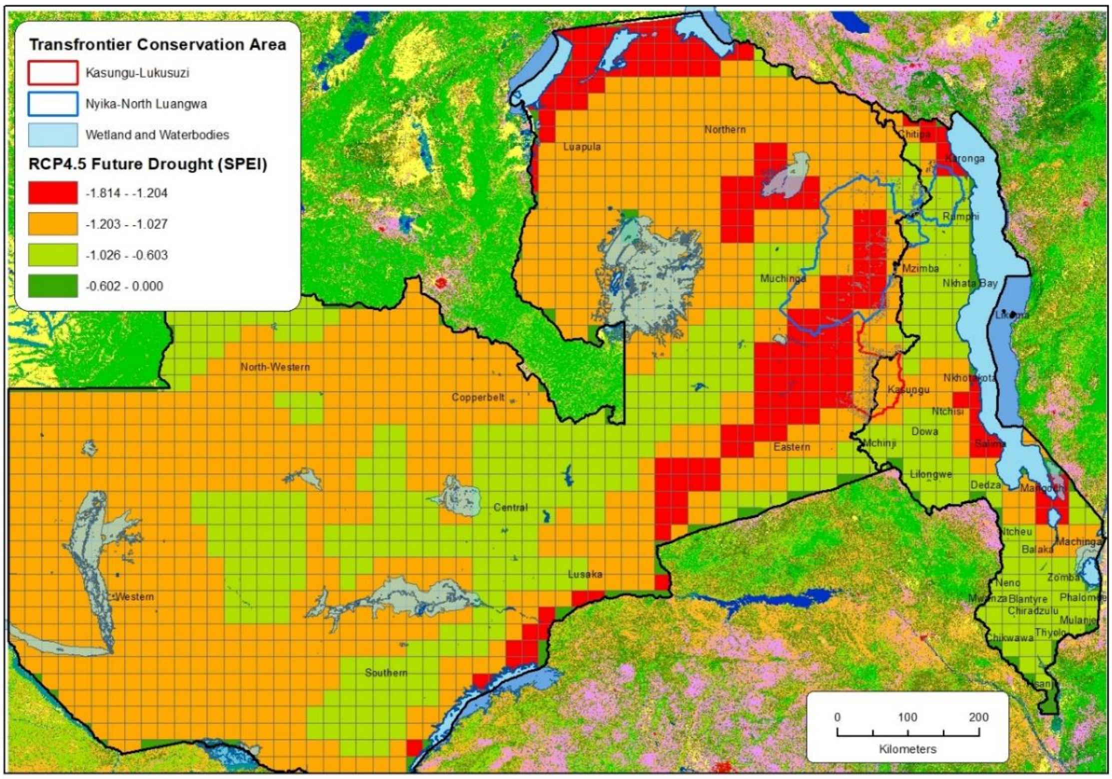

Figure A.1.3: Map of Regional Future Drought (RCP4.5)

(Data sources: National Boundaries: GADM V4.1; Land Cover: © Copernicus Service Information 2019)

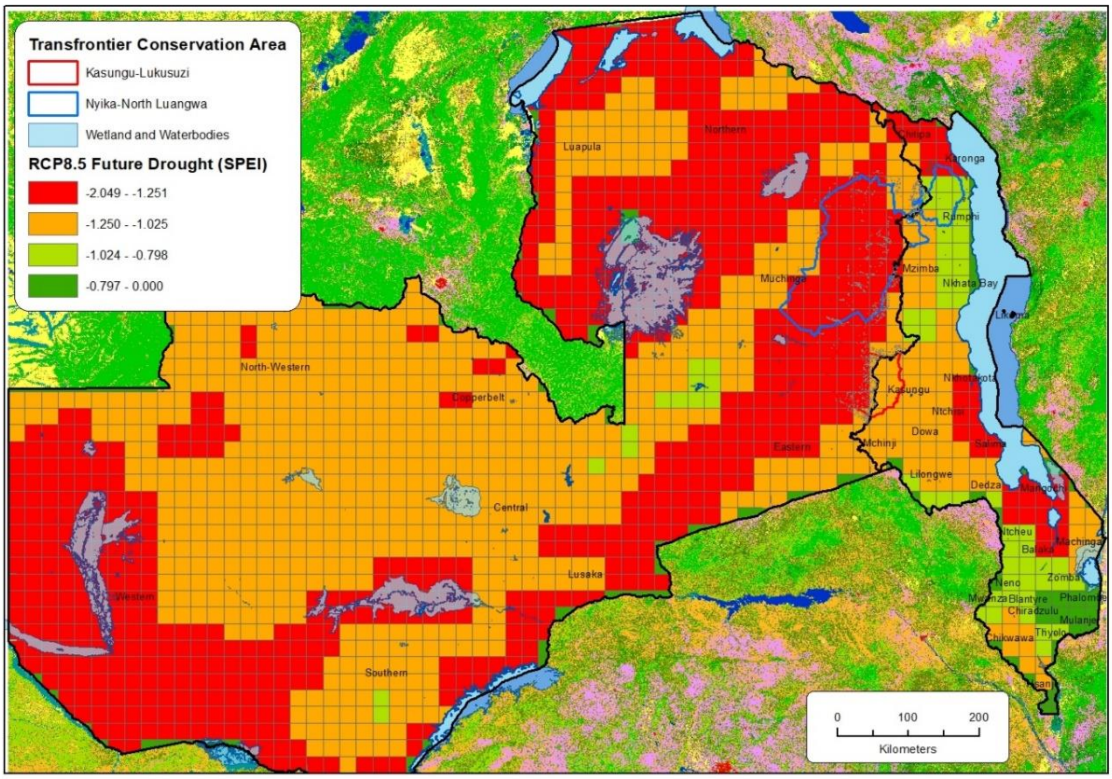

Figure A.1.4: Map of Regional Future Drought (RCP8.5)

(Data sources: National Boundaries: GADM V4.1; Land Cover: © Copernicus Service Information 2019)

Appendix 2: Regional Bivariate Maps

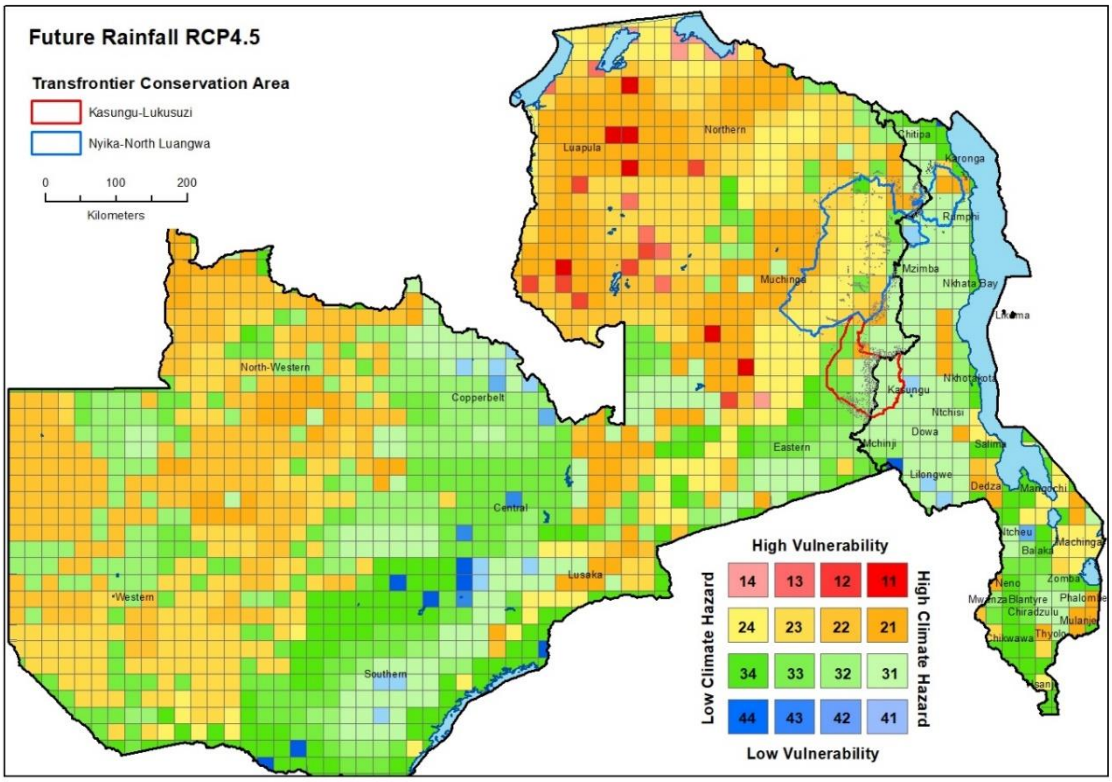

Figure A.2.1: Regional Bivariate Future Rainfall Vulnerability Map (RCP4.5)

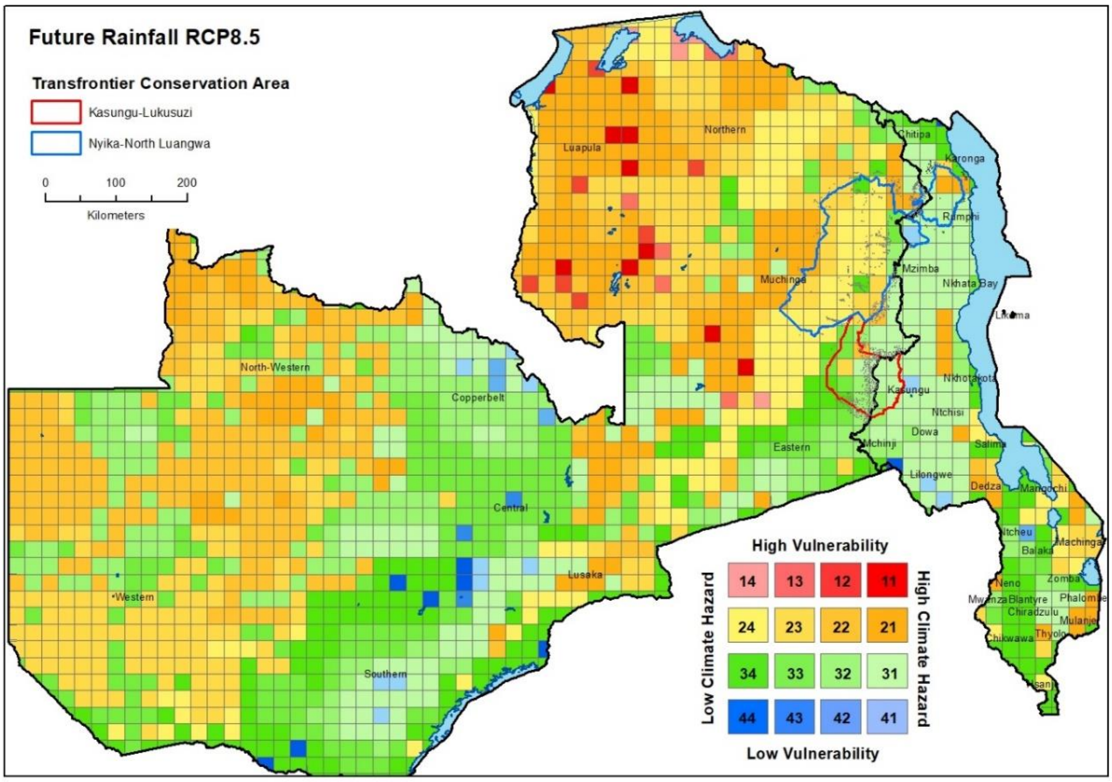

Figure A.2.2: Regional Bivariate Future Rainfall Vulnerability Map (RCP8.5)

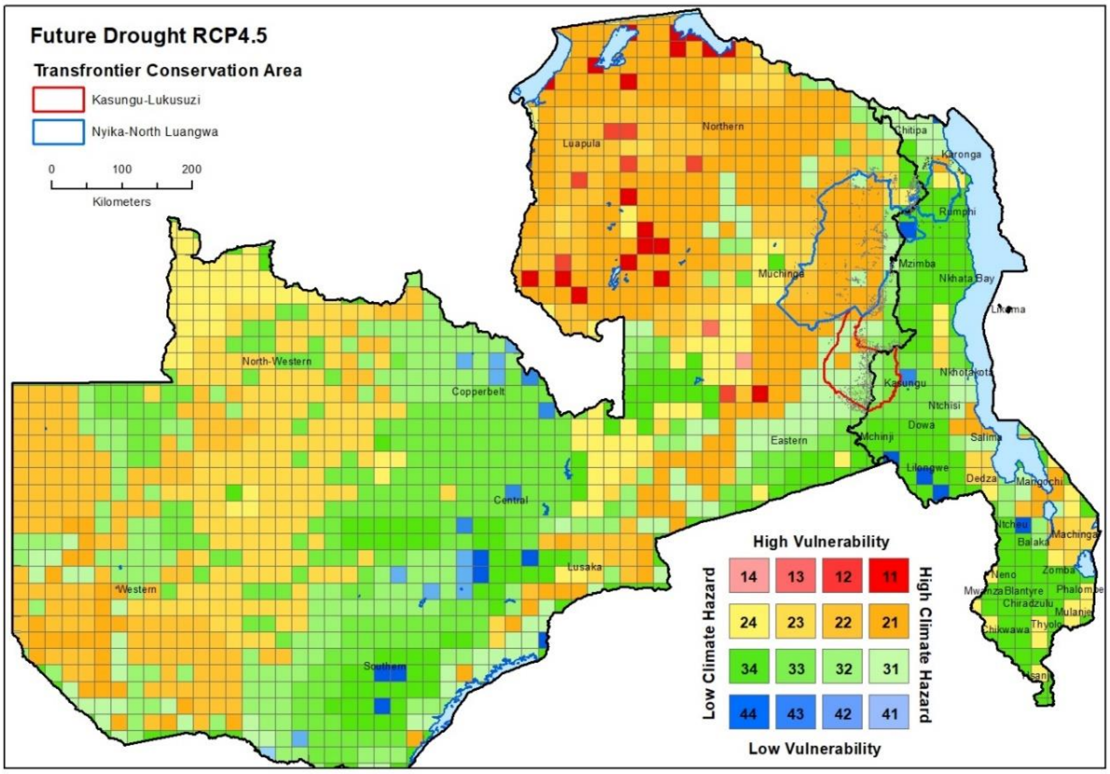

Figure A.2.3: Regional Bivariate Future Drought Vulnerability Map (RCP4.5)

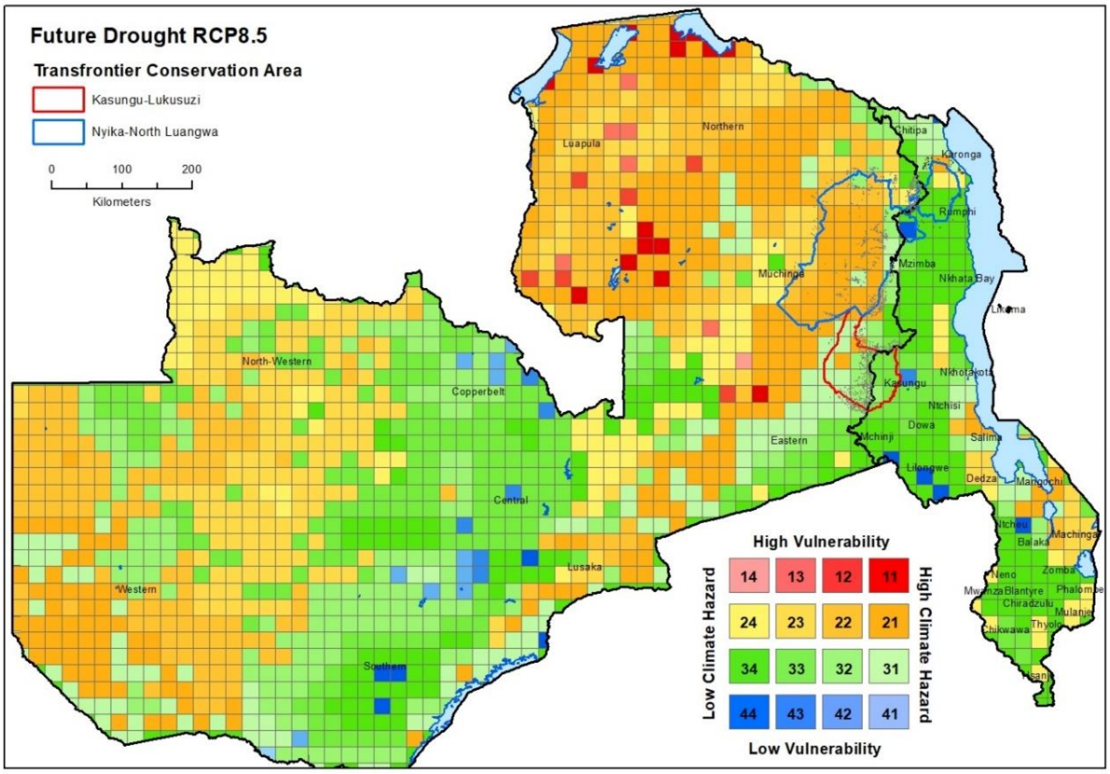

Figure A.2.4: Regional Bivariate Future Drought Vulnerability Map (RCP8.5)