Assessing and managing climate change related risks to the Tana River Basin, Kenya

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Abstract

The Tana River Basin is one of the most economically-important and ecologically-diverse river basins in Kenya. It contains internationally-recognised biodiversity areas. It is also central to Kenya's future development agenda. However, projected climate change may undermine this agenda and threaten the basin's unique ecosystems. The changing climate, along with issues arising from planned socio-economic development, is likely to increase the existing problems of limited water and land resources. This research projects the impacts of climate change upon three key sectors (water, biodiversity and agriculture) within the Tana River Basin in order to inform national climate change adaptation plans using a range of climate scenarios and models. Once the projected effects of climate change on the three sectors were determined, possible adaptation measures were identified. Then, potential trade-offs or synergies between sectors and adaptation measures were determined.

All three sectors are projected to be significantly affected by climate change, even under the lowest levels of warming. Projected increases in precipitation of basin-average of around 12-16% will lead to greater water availability across the basin, but these increases are unlikely to outweigh the increases in water demand caused by the rapidly growing population and industrial development. By contrast, higher temperatures are projected to substantially reduce species richness (of a basin and taxa-average of 30-42% of species at risk of local extinction) and yields of most major crops (including maize, wheat and sugarcane).

As climate change is a cross-cutting and multifaceted challenge, results from the individual sectors were combined using GIS and compared to government development plans. Hotspots of projected climate change impacts and development plans were identified in the Upper Tana and Tana Delta regions. This is the first cross-sectoral GIS analysis of the impacts of climate change and development plans in the Tana River Basin and contributes to a greater understanding of impacts and adaptation options in Kenya.

List of Acronyms and Abbreviations

AET	Actual Evapotranspiration
AOC	Area of concern
BAU	Business as usual
CMIP5	Coupled Model Intercomparison Project Phase 5
CR	Critically endangered
CRU	Climatic Research Unit
CWI	Cloud Water Interception
CWP	Crop water productivity
DSS	Decision support system
EBA	Endemic Bird Area
ECE	Extreme climatic event
EN	Endangered
ENSO	El Nino Southern Oscillation
ET	Evapotranspiration
FAO	Food and Agriculture Organisation
FIESTA	Fog Interception for the Enhancement of Stream Flow in Tropical Area
GAEZ	Global agro-ecological zones
GBIF	Global Biodiversity Information Facility
GCM	Global Climate Model
GDP	Gross domestic product
GGCM	Global Gridded Crop Model
GHG	Greenhouse gas
GIS	Geographical Information System
GoK	Government of Kenya

HEP	Hydro-electric Power
IAM	Integrated Assessment Model
IOD	Indian Ocean Dipole
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
ITCZ	Inter-Tropical Convergence Zone
IUCN	International Union for Conservation of Nature
JICA	Japan International Cooperation Agency
KWCA	Kenya Wildlife Conservancies Association
LAI	Leaf Area Index
LAPSSET	Lamu Port South Sudan Ethiopia Transport corridor
LC	Least concern
LUCC	Land Use and Cover Change
LUH2	Land Use Harmonisation V2
MCM	Million cubic metres
MEA	Millennium Ecosystem Assessment
MENR	Ministry of Environment, Water and Natural Resources
MODIS	MODerate Resolution Imaging Spectroradiometer
NAPA	National Adaptation Programme of Action
NCCAP	National Climate Change Action Plan
NDC	Nationally Determined Contributions
NDMA	National Drought Management Authority
NT	Near threatened

PA	Protected Area
PET	Potential Evapotranspiration
PSS	Policy Support System
RCP	Representative Concentration Pathway
SD	Standard deviation
SDG	Sustainable Development Goal
SDM	Species distribution model
SSP	Shared Socio-economic Pathway
SWAT	Soil and Water Assessment Tool
TDIP	Tana Delta Irrigation Project
TRMM	Tropical Rainfall Measuring Mission
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VCF	Vegetation Continuous Field
VU	Vulnerable
WDPA	World Database on Protected Areas
WMO	World Meteorological Organisation
WRMA	Water Resources Management Authority
WWF	World Wide Fund for Nature

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Chapter 1 Introduction

1.1. Background and Motivation

There is a general scientific consensus that anthropogenic climate change will affect all sectors, with effects already being observed in sensitive areas (IPCC, 2014). Future climate change is projected to have a range of effects on the natural environment as well as human socio-economic systems. The effects of climate change are not confined to any one sector, so it is important to consider cross-sectoral impacts (Warren, 2011; Berry *et al.*, 2015; Harrison *et al.*, 2016; Challinor *et al.*, 2018a; Harrison *et al.*, 2018). Changes in one sector can lead to changes in another, either directly or indirectly (Nicholls and Kebede, 2012). The magnitude of the impacts of climate change are projected to vary across the world, possibly leading to hotspots of impacts or conflicts between uses and users. As stated by Harrison *et al.* (2018), regardless of the trajectory of the warming, climate change will have significant implications for human and environmental systems.

Despite Sub-Saharan Africa having had the smallest contribution to global greenhouse gas emissions (Kula *et al.*, 2013), it is disproportionately vulnerable to the effects of climate change (Gelorini and Verschuren, 2012). Mileham *et al.* (2009) showed that, over the 20th century, mean surface temperatures across Africa rose by approximately 0.7°C; which is 0.1°C above the global average. Now, global temperatures are projected to have increased by over 1°C (Haustein *et al.*, 2017). de Wit and Stankiewicz (2006) argue that climate change poses one of the greatest threats to poverty eradication in Africa and changes in surface water supply will be particularly significant in exacerbating the threat. Huang *et al.* (2017) found that drylands are projected to experience greater risks from climate change than tropical regions.

Many countries face the challenge of socio-economic development in addition to responding to the threats of climate change. Many river basins in the developing countries of Africa are undergoing substantial expansion of irrigation for agriculture and dams for hydropower in order to meet national targets for socio-economic growth (Baker *et al.*, 2015). However, climate change may significantly undermine these goals. The Tana River Basin in Kenya is an example of a basin where significant development targets for hydropower, domestic water provision and irrigation are planned as part of Kenya’s national development blueprint, the Vision

2030 (GoK, 2007). However, the Tana River Basin is already experiencing a range of threats, including competing water demands, sensitive ecosystems and downstream impact of upstream development, which may be exacerbated by climate change. Decision-makers will need to develop climate resilience and sustainable solutions to these challenges. These cross-cutting problems will have implications for poverty alleviation and socio-economic development.

East Africa is a particularly interesting and important region because the current climate change projections vary greatly on the expected changes to precipitation (Yang *et al.*, 2015; Dunning *et al.*, 2017). Unlike other countries in East Africa, Kenya has a clear development agenda, the Kenya Vision 2030 (GoK, 2007), that they are currently in the process of implementing through a series of mid-term plans and flagship projects. The Government of Kenya (GoK) identifies climate change as a significant challenge to attaining Vision 2030. However, there is little consideration of climate change in existing sectoral development plans. Climate change is recognised as a problem but adaptation is not yet embedded into plans, which may affect the suitability of these proposals. The fact that clear plans, such as the Vision 2030 (GoK, 2007) and the National Spatial Plan (GoK, 2017), are available makes possible an investigation into how future development and climate change adaptation may interact. It should be noted that Rwanda has progressed much further with mainstreaming their climate change adaptation plans than Kenya and the other East African countries. In addition to this, Kenya's National Adaptation Plan (GoK, 2016) recognises the need to expand and improve upon existing climate change modelling work.

Within Kenya, the Tana River Basin plays a vital role in the country's economy; supplying 80% of Nairobi's drinking water and around 70% of Kenya's hydropower energy through its dams. The basin is also a biodiversity hotspot and its delta ecosystem was recently classified as a Ramsar designated wetland (Ramsar, 2012). The Tana River Basin is also of fundamental importance to the socio-economic development of Kenya as major infrastructure investments are planned in this basin.

The limited amount of previous research on the projected impacts of climate change on the Tana River Basin that exists has mainly focused on hydrology and ecosystem services (see Chapter 2, Section 8). This study builds on previous work by considering multiple sectors, including agriculture which has not previously been investigated, and comparing the projected impacts to the development plans.

1. 2. Introduction to the Tana River Basin

1.2.1 Physical Characteristics

The Tana River Basin, shown in Figure 1-1, is located in South-eastern Kenya and covers around 95,000km²; 20% of the country's total land area. At approximately 1000 km from source to mouth, the Tana River is the longest river in the country, originating from the southern slopes of Mount Kenya and flowing into the Indian Ocean through the Tana Delta. The tributaries that join the main river in the mid to lower reaches are seasonal (known as lagas), making the Tana the only permanent river in the region. In its lower reaches, the Tana's floodplains vary between widths of 2km to around 42km (Terer *et al.*, 2004). This low-lying floodplain is predominately used for grazing. However, the land type varies greatly within the Tana catchment area, with the highest elevations classified as humid, central and coastal areas as semi-arid and the remainder as arid land.

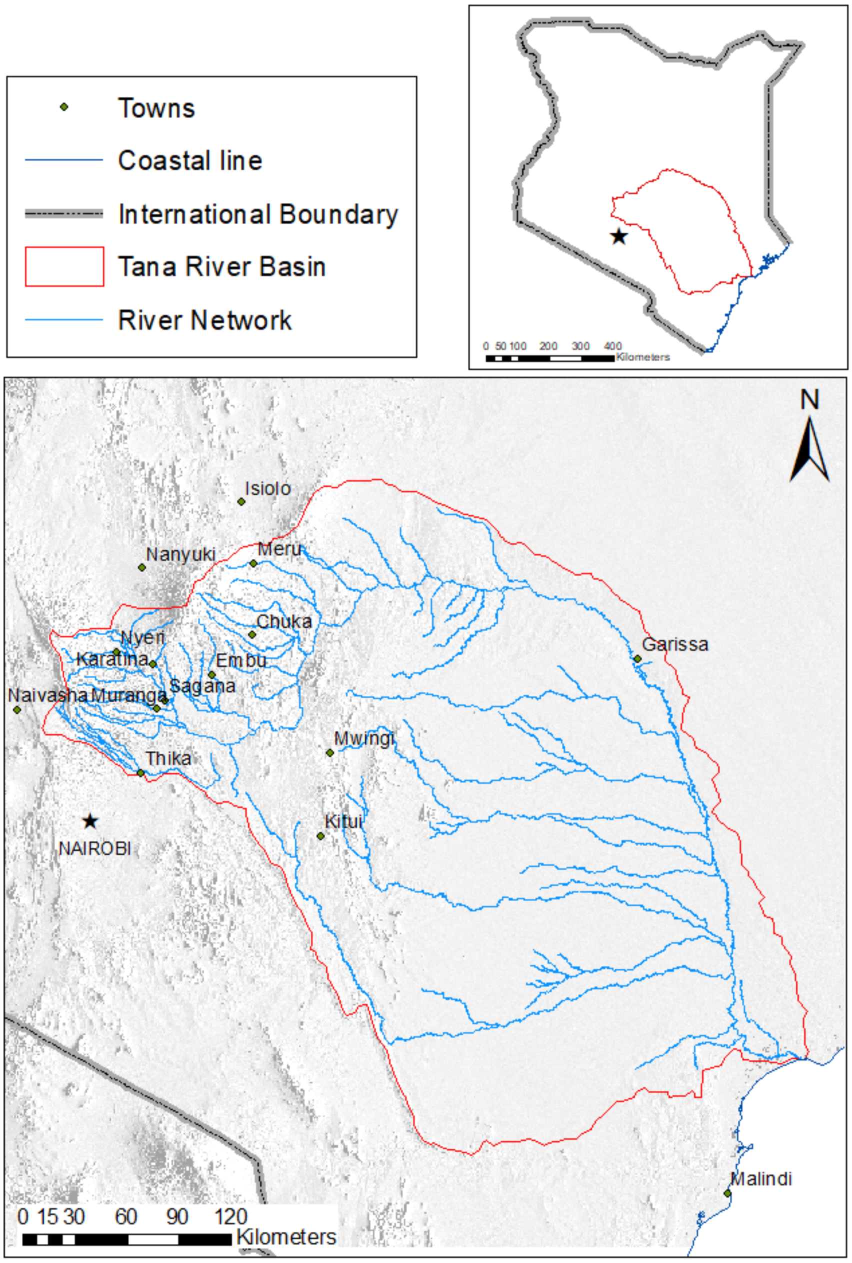

Figure 1-1 The Tana River Basin, with the location of Kenya's capital city, Nairobi, and major towns marked on

1.2.2 Water Resources

The National Water Master Plan 2030 (MENR, 2013a) estimates the annual surface water resources for the Tana Basin as 5,858 million cubic metres per year (MCM/year). The available groundwater resources are significantly lower, at around 675 MCM/year. The report (MENR, 2013a) stated that groundwater resources are expected to decrease in the future, whereas surface water resources are likely to increase. The proportion of the current (2010) water demand for each sector is shown in Table 1-1. Irrigation accounts for the largest proportion water demand. Domestic water supply also accounts for a relatively large proportion of the total. Wildlife, industry and fisheries account for a very small proportion of current water use within the Tana River Basin.

Table 1-1: Water demands by subsector for the Tana Catchment Area for the year 2010. Source: National Water Master Plan Report (JICA, 2013). Ref. Main Report Part F, Section 3.3.

Subsector	**Proportion of water demand**
Domestic	16%
Industrial	0.6%
Irrigation	78%
Livestock	3.8%
Wildlife	0.1%
Fisheries	1%

Water resources within the basin are highly spatially and temporally variable. As well as experiencing drought conditions, the Tana River floods annually. Prior to dam construction, the Tana flooded biannually, often up to a depth of 3 metres. However, as noted by Hughes (1990), prior to dam construction, the flood depth varied considerably, with some years seeing depths well below 3 metres. Flooding of the Tana is important to the natural environment of the lower basin, supporting a variety of ecosystems, including grasslands, riverine forests and mangroves.

Currently, the Tana River Basin supplies Nairobi with hydropower and nearly all of its domestic water uses (Baker *et al.*, 2015). There are five hydropower stations and reservoirs located on the upper reaches of the Tana, which are vital to the country's energy production. The first three dams were built along the Tana between 1968 (the Kindaruma Dam) and 1978 (the Gitaru Dam). Two additional reservoirs, the Masinga and Kiambere, were constructed during the 1980s. Their combined annual power generation accounts for approximately 70% of the country's electricity supply from hydropower. Rowntree (1990) demonstrates the importance of this to Kenya, showing that, without hydroelectric power, the country would be entirely reliant on imported coal and oil. It is widely accepted that dam construction can have a range of positive and negative impacts on the local environment. Maingi and Marsh (2002) suggest that, after the construction of these dam projects, the river was left unregulated. Resettlement and displacement issues have been raised by dam construction.

1.2.3 Biodiversity

The Tana River Basin is extremely important in terms of biodiversity and contains national reserves and national parks (Figure 1-2). In total, around 20% of the basin is classified as protected area (PA). The full list of PAs within the basin and their classification can be seen in Table AI-1 in Appendix I (IUCN and UNEP-WCMC, 2016). In the upper reaches of the Tana River, the slopes of Mount Kenya are protected as a National Park or as forest reserve. The north of the basin also includes PAs adjacent to the main Tana River, such as Meru and Kora National Parks. Much of the floodplain adjacent to the lower reaches of the river is protected as community nature reserves. This area also contains the Tana River Primate Reserve. Tsavo East National Park is located in the southwest of the basin, furthest away from the Tana River itself. In the wet seasons, a tributary of the Tana flows through this area, which is visible on Figure 1-2. Likewise, South Kitui National Reserve relies on a seasonal tributary of the Tana. The greater Tsavo ecosystem, which includes both Tsavo East and South Kitui as well as PAs outside of the basin boundaries, is praised as one of the few remaining true wildernesses in Kenya. Tsavo East is one of the oldest PAs for wildlife in the country (Odhengo *et al.*, 2014). There are also many small forest reserves within the basin.

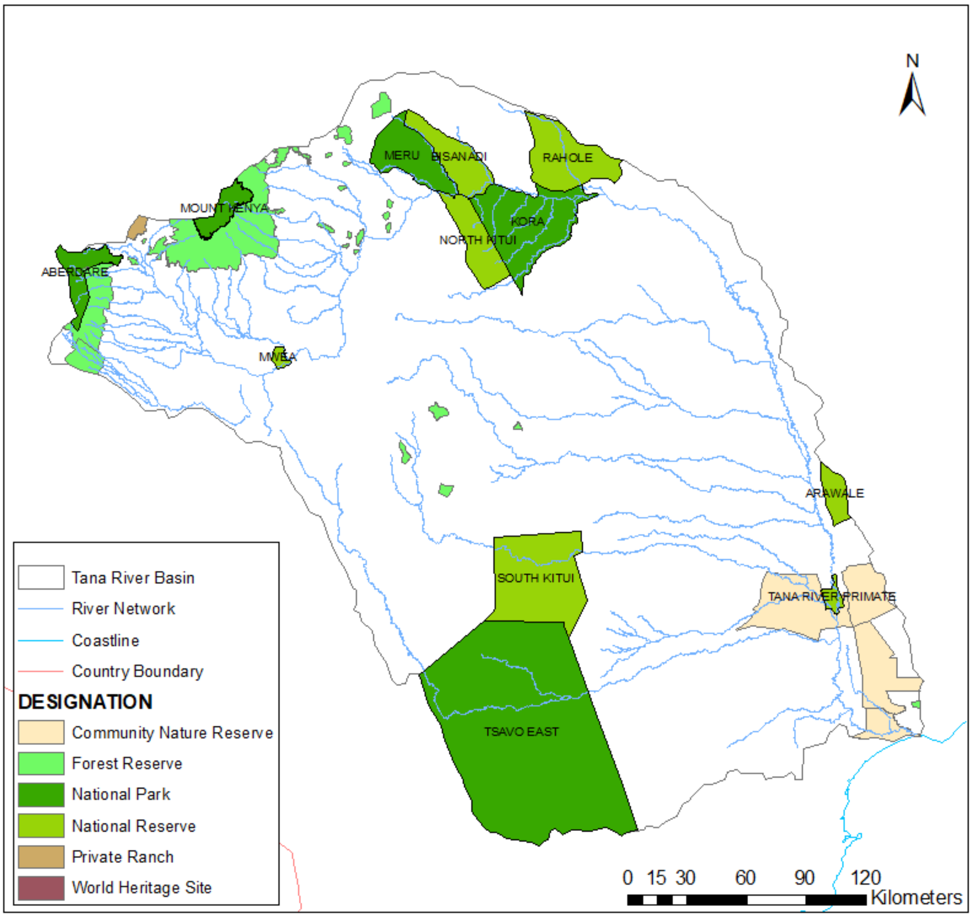

Figure 1-2: Location of protected areas within the Tana River Basin, with the national parks and national reserves labelled. Data on protected areas from the World Database of Protected Areas - IUCN and UNEP-WCMC (2016).

The floodplain forests of the lower Tana form part of the Eastern Arc and Coastal Forests of Eastern Africa biodiversity hotspot, which have been argued to be a refugium for wildlife during past geological periods when climate was too hostile for forest development in most tropical countries. The riparian forests are maintained by groundwater and alluvial sediments deposited during the seasonal floods. The floodplain forests are also known to home two critically endangered primate species: the Tana River Red Colobus and the Tana River Mangabey, which are both endemic to the area (Terer *et al.*, 2004).

Additionally, the Tana River Delta is known to have a high number of bird species and is designated as an Important Bird Area (Bennun and Njoroge, 2000) and Ramsar wetland (Ramsar, 2012). As well as having a rich native avifauna, Kenya is located on a major migration pathway for birds travelling from the Palaearctic to their non-breeding grounds in sub-Saharan Africa (Muriuki *et al.*, 1997). Fanshawe and Bennun (1991) have argued that Kenya's rich birdlife gives the country national and international conservation responsibilities. This shows that the Tana River Basin is of global conservation importance and understanding any future changes in its ecosystems is paramount. In its Vision 2030, the Government of Kenya (2007) recognises the importance of maintaining a high level of biodiversity, both for the environment and to encourage tourism. Velarde *et al.* (2005) showed that over 75% of tourists visit Kenya primarily for nature tourism, so changes to the biodiversity could have important consequences for the economy.

1.2.3.1 Ecosystem Services

The Tana River Basin provides ecosystem services at local levels and beyond. Ecosystem services can be defined as the benefits that humans and society get from natural ecosystems (MEA, 2005). The mangrove forests in the delta act as natural flood protection, and the delta itself contains important fisheries and provides water for crops and livestock. Other ecosystem services provided by the Tana River Basin include drinking water and, indirectly, electricity production. Finlayson *et al.* (2005) showed that these hydrological ecosystem services contribute to poverty alleviation and human well-being. In Kenya, many vulnerable groups directly rely on wetlands and the services they provide.

The biodiversity of the Tana River Basin also provides cultural ecosystem services through nature-based and wildlife tourism. PAs provide recreational ecosystem services which can enhance human well-being. Globally, PAs are estimated to attract 8 billion visitors a year (Balmford *et al.*, 2015). Visitor expenditure can also lead to economic benefits for the local population.

1.2.4 Agriculture

The Tana River Basin contains a variety of agricultural crops. The upland areas in the north of the Tana River Basin contain economically-important coffee growing regions, including around Embu, Nyeri and Meru (Laderach, 2010). In addition, the mountainous region contains important tea plantations and horticulture. The main crops grown under rain-fed production along the Tana River in its mid and lower reaches are maize, green grams, cowpeas and water melon (NDMA, 2017). Other major crops include mangoes, bananas and tomatoes (NDMA, 2017). Cowpea is the most important grain legume around the coastal region (Karanja, 2006).

As shown in Figure 1-3, much of the agricultural activity (crops) is concentrated in the upper, western area of the basin, but some smaller farms are seen near to the main Tana River and its seasonal tributaries. A range of agricultural types are present in the basin, including both rain-fed and irrigated agriculture. As shown by the proportion of the water given to irrigation in Table 1-1, the basin is extremely important for agricultural production. However, large-scale irrigation projects have experienced varying levels of success because of climate variability in the region (see Chapter 6, Section 2.1).

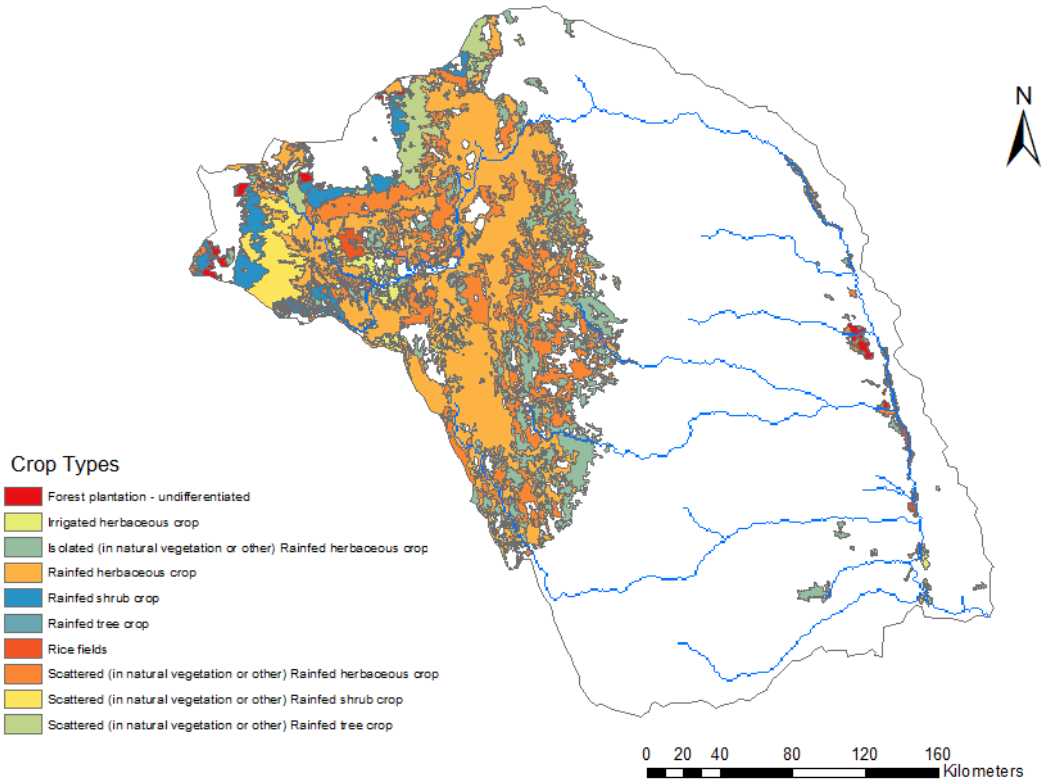

Figure 1-3: Current cropland in the Tana River Basin, data from World Resources Institute (2007)

Agriculture in Kenya is still largely rain-fed, so it is extremely dependent on the climate. Kenya's farming system still consists of predominantly small-scale farms. Small-scale farmers in Africa already face the challenges of climate variability and many will have coping responses already in place for periods of drought. Agriculture in Kenya consists of both food crops and cash crops, both of which are important to the country's economy. The top ten food and agricultural commodities produced in Kenya in terms of area harvested, yield and gross production value can be seen in Table 6-1 (FAOSTAT, 2017). Maize is the largest crop in Kenya in terms of area harvested and gross production value, whereas sugarcane is top in terms of yield. The primary crops consumed in Kenya are: maize, wheat, beans, potatoes, plantains, and rice (Ariga *et al.*, 2010). Brooks *et al.* (2009) note the importance of maize, both as staple crop and socially. However, maize production has suffered from the droughts.

In recent decades, the frequency of droughts and maize crop failures have increased in the drylands of Kenya. Following the drought of 2000 in central and eastern Kenya, maize yields dropped by 36%. Droughts in Kenya frequently lead to crop yield losses of between 30 and 40%. Cropland close to forests are also put at risk from forest fires in these dry periods. Agricultural losses due to drought often result in a significant proportion of the population relying on food relief. Farmers have been encouraged to crop millet and sorghum instead, as these plants are more drought tolerant. This shows that there is already evidence of recent climate variability affecting crops in the country. A recent report from the Government of Kenya (2017) explains that most cereal crops experienced declines in production in recent years, but the crops sector was boosted by a higher output of wheat. The production of beans has also declined but the production of Irish potatoes has increased.

Table 1-2: Top 10 crops in Kenya based on three different measures: area harvested, yield and gross production value. Data from FAOSTAT (2017) based on 2014 values.

Rank	**Area harvested (ha)**		**Yield (hg/ha)**		**Gross Production Value (constant 2004-2006 1000 I$)**	
1	Maize	2116141	Sugar cane	897418	Maize	497693
2	Beans, dry	1052408	Carrots and turnips	434360	Tea	473359
3	Cow peas, dry	281877	Cabbages and other brassicas	309165	Bananas	463180
4	Pigeon peas	276124	Bananas	277056	Mangoes, mangosteens, guavas	453755
5	Sorghum	213520	Strawberries	269863	Beans, dry	370455
6	Tea	203006	Pineapples	269064	Potatoes	274442
7	Wheat	147210	Watermelons	245597	Sugar cane	210483
8	Millet	138829	Avocados	188804	Tomatoes	163817
9	Potatoes	115604	Tomatoes	180698	Avocados	151545
10	Coffee, green	110000	Lettuce and chicory	174750	Pigeon peas	146658

1.2.5 Demographic Characteristics

The Tana River Basin is vital not only to Kenya's economy, but also to its population. Based on the 2009 Census (GoK, 2010a), the population of the Tana Catchment Area is thought to be 5.7 million, approximately 15% of the total population of Kenya (JICA, 2013; MENR, 2013a). There are a number of different tribal populations within the Tana River Basin (Baker *et al.*, 2015). Traditionally agricultural peoples, such as the Kikuyu, are found within the upper Tana whereas pastoralists, such as the Pokomo and Orma tribes, dominate the lower Tana. It has been estimated that over a million people either directly or indirectly depend on the Tana's flood regime (Terer *et al.*, 2004).

Population growth rates in the Tana Basin are relatively low compared with other catchment areas in the country. However, this population increase is still likely to put increased pressure on water and land resources. Kenya is already experiencing pressures from water scarcity and a growing population (Maingi and Marsh, 2002). The population growth is particularly significant in the upper basin, where higher numbers of people are leading to land shortages and increased land degradation (Tanui, 2006). The Japan International Cooperation Agency (JICA, 2013) produced a report, during the development of the National Water Master Plan 2030, which projected population within the Tana catchment would reach 8.4 million by 2030.

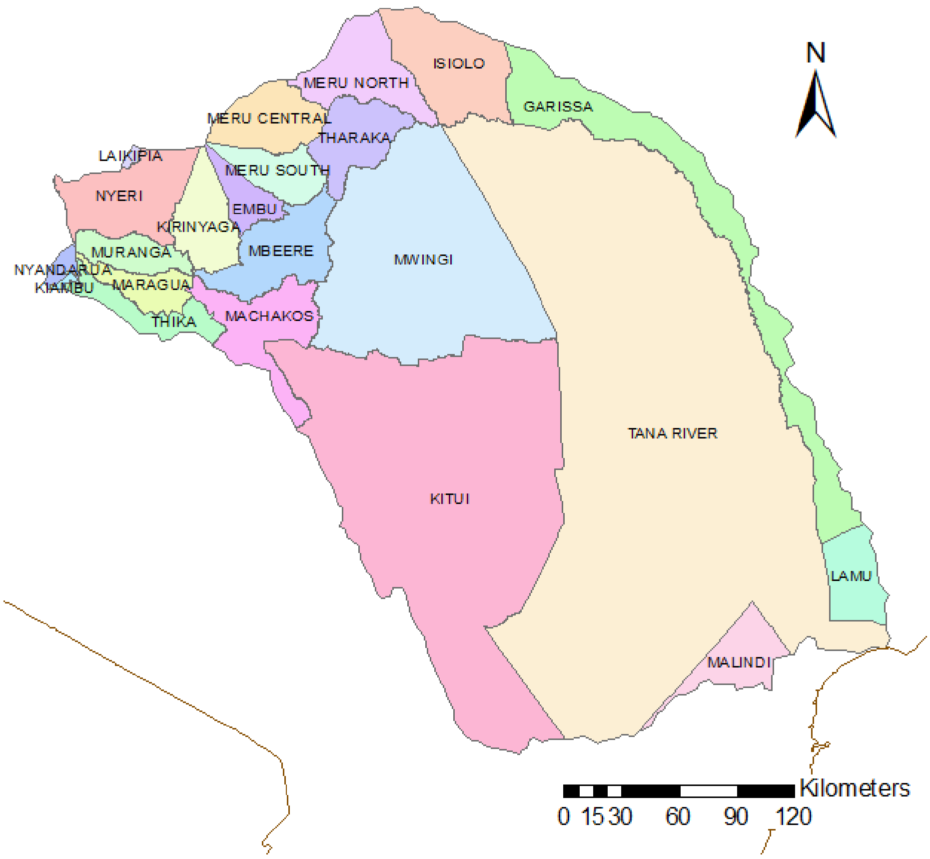

Figure 1-4: Administrative areas (or districts) within the Tana River Basin. District boundaries data from World Resources Institute (2007).

Peoples' livelihoods within the basin comprise a wide range of activities, including fishing, agriculture and pastoralism, as well as work related to conservation and employment within urban areas (MENR, 2013a). Figure 1-5 shows the livelihood zones in the Tana River Basin (from FEWSNET, 2011). The northern areas of the basin are dominated by croplands and the central and lower Tana are dominated by pastoralism. Mixed farming occurs within the coastal zones.

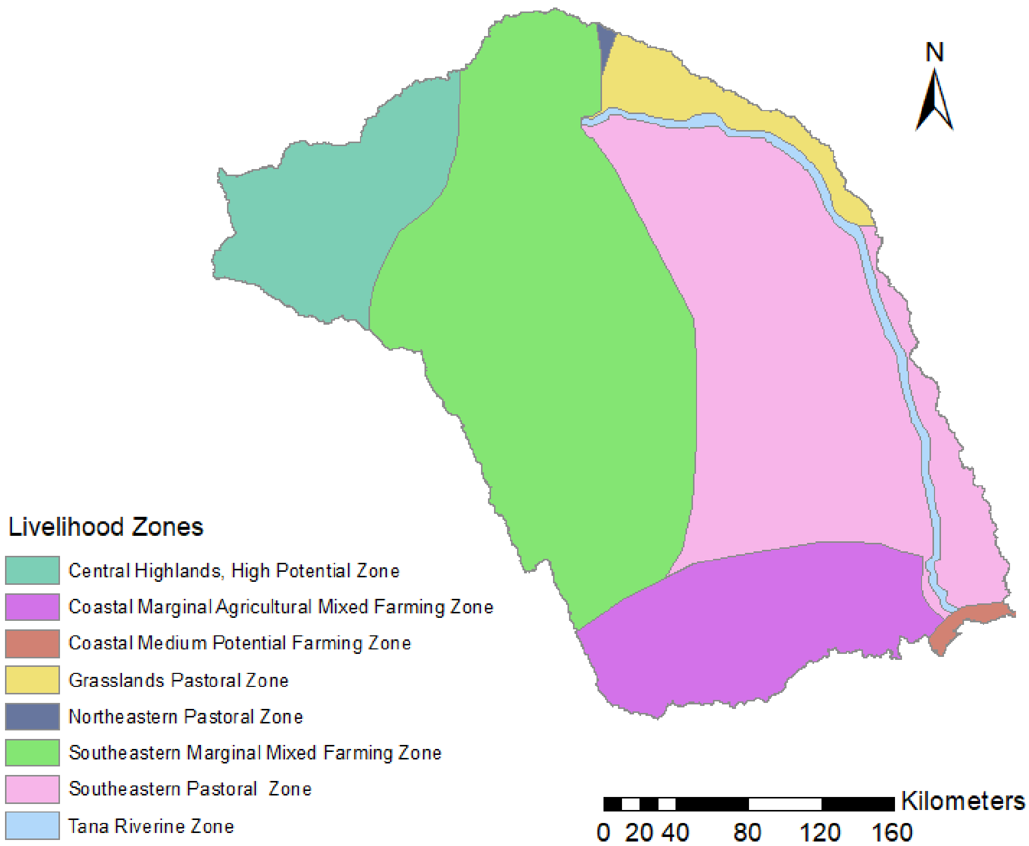

Figure 1-5: Livelihood Zones within the Tana River Basin. Livelihood zones data source: Famine Early Warning Systems Network, FEWSNET, 2011 (http://www.fews.net/)

The Vision 2030 (GoK, 2007) includes various flagship projects for the Tana River Basin. These include additional hydropower dams and large-scale irrigation schemes (GoK, 2013). In addition, the Lamu Port –South Sudan-Ethiopia Transport (LAPSSET) corridor project will include major road and railway lines that run along the eastern edge of the basin.

1.3. Aim and Objectives

This research aims to project the impacts of climate change upon the Tana River Basin for the 2050s in order to inform national climate change adaptation plans. This will involve modelling the effects of climate change on the water, biodiversity and agricultural sectors and examining the interactions between the sectors and possible adaptation responses to climate change. The timescale of the 2050s was chosen as the main focus of this study because it is a mid-term time horizon which is relevant to the policies and plans set out by the GoK. However, the 2070s was also considered in Chapters 3 & 4, and the changes in species' range and richness over the 2020s-2080s were considered for biodiversity in Chapter 5. The results of Chapters 3 & 4 further justify the choice of the 2050s for the remaining chapters and analyses (which is explained in Chapter 3, Section 6).

Within this, specific objectives are to:

(i) establish the range of projected climate change impacts on (a) water, (b) agriculture and (c) biodiversity conservation in the Tana River Basin across climate models and emissions pathways for the 2050s (2041-2060),

(ii) to examine the extent to which climate change adaptation is considered in existing policies,

(iii) to identify hotspots of trade-offs or synergies between the projected impacts of climate change in the three sectors (water, biodiversity and agriculture), the possible adaptation measures appropriate for each sector and existing development plans.

(iv) to investigate the uncertainties in projected climate change impacts that arise from the different GCMs and RCPs in order to inform robust policy and adaptation plans.

1.4 The value of this approach

This research is the first cross-sectoral GIS analysis of the projected impacts of climate change and development plans in the Tana River Basin. More detail on how this research addresses gaps in the current understanding is provided in Chapter 2, Section 8. The various impacts of climate change across the water, biodiversity and agriculture sectors, as well as the impacts of changes to land use, are interlinked. Given the interactions between the impacts and possible climate change adaptation measures within the sectors, an integrated research approach is beneficial. The importance of cross-sectoral interactions for addressing the impacts of climate and/or land use change has been widely acknowledged (Berry *et al.*, 2015; Dunford *et al.*, 2015; Van der Esch *et al.*, 2017).

1.5 Thesis Outline

This thesis comprises nine chapters including the introduction and conclusion chapters. Chapter 2 provides a review of the current knowledge and literature on the impacts of climate change on water resources, biodiversity and agriculture. An overview of the different methods used in this research is presented in Chapter 3. Chapters 4 to 7 each address the impacts of climate change on a sector from the first research question presented in section 1.3.

In Chapter 4, the projected changes to temperature and precipitation in the Tana River Basin are analysed.

In Chapter 5, other key hydrological variables (AET, water balance, water stress and runoff) are considered, again using the WaterWorld model to project future changes.

In Chapter 6, the Wallace Initiative Database is used to examine projected changes to the distribution of plants and animals as a result of climate change.

In Chapter 7, projected changes to agricultural yields and suitable climate space for selected crop, fruit and forestry species are analysed. Then, these results, information from GoK development plans and the results of the previous chapters are combined using GIS in order to examine the hotspots of climate change impacts within the basin.

In Chapter 8, an interdisciplinary discussion of the findings for each sector and recommended possible adaptation measures are presented. Then, the chapter discusses the interactions between the different sectors; including the potential trade-offs and synergies between different sectors and recommended adaptation measures.

Chapter 2 Literature Review

2.1 Introduction

This chapter synthesizes relevant literature in order to assess projected climate change and its impacts on the hydrological cycle, agriculture and biodiversity throughout the 21st Century, both globally and for the East Africa region. It will also examine the current state of knowledge of cross-sectoral climate change impact studies. The chapter is organised as follows: first, global-scale changes are considered (Section 2), then impacts on East Africa (Sections 3 and 4), then the threats other than climate change (Section 5) before the context of Kenya (Section 6) and the Tana River Basin (Section 7) specifically are discussed. The final section identifies and considers knowledge gaps and how these are addressed by this thesis (Section 8).

2.2 Global Scale Climate Change Impacts

2.2.1 The Hydrological Cycle

The vulnerability of the hydrological cycle to changes in climate has been widely acknowledged (Vorosmarty *et al.,* 2005; Gosling and Arnell, 2016). At the global scale, climate change is expected to reduce the volume of both renewable surface and groundwater resources (Kundzewicz *et al.*, 2008, Jiménez Cisneros *et al.*, 2014). Fung *et al.* (2011) showed that beyond 2°C of temperature rise, elevated water stress is projected, as climate becomes the major limiting factor in water availability. Jiménez Cisneros *et al.* (2014) determined that the projected impacts of climate change on freshwater resources increase considerably with higher greenhouse gas concentrations and temperature rises. The different elements of the hydrological cycle are discussed in this section.

2.2.1.1 Precipitation

Global trends in precipitation are not as readily apparent as patterns of temperature change, partly due to regional variations masking global signals (Rowell, 2012). Precipitation changes are more spatially and temporally variable than temperature (Kundzewicz and Doll, 2009). However, Zhang *et al.* (2007) compared model results and observations for the 20th Century and concluded that climate change is already driving changes in precipitation. In areas such as southern Africa and Australia, both model projections and observational data show increases in precipitation. By contrast, northern Africa and Southeast Asia show decreases in precipitation. Large reductions in the amount of winter precipitation falling as snow in mountainous and high-latitude regions are projected as global temperatures increase (Barnett *et al.*, 2005).

Alterations in the distribution of precipitation between high and low frequency events will also prove extremely important (Allen and Ingram, 2002). Overall, the global hydrological cycle is projected to intensify (Fung *et al.*, 2011; Arnell and Gosling, 2013). Precipitation is projected to be more concentrated in heavy rainfall events, while a reduction in moderate precipitation events are likely to be observed. Hegerl *et al.* (2004) compared two different models to show that increases in precipitation on the wettest day are greater than the increases in the mean precipitation change. Higher intensity rainfall may increase erosion and the occurrence of natural disasters, such as landslides and floods (Nearing *et al.*, 2004).

2.2.1.2 Glaciers

As global temperatures increase, glacial ice loss will continue. Glaciers are extremely sensitive to changes in climate and changes are already being observed. Reductions in glacier area have been observed in all areas in recent years (Vaughan *et al.*, 2013; Gardner *et al.*, 2013), along with the disappearance of glaciers in some regions. Knoll and Kerschner (2009) found losses from glaciers in Italy’s South Tyrol had accelerated since 1983, but that the exact changes varied greatly amongst the individual glaciers. Huss and Fischer (2016) found that small glaciers in the Swiss Alps are particularly sensitive to changes in climate. Their results projected that over half of small glaciers in Switzerland will disappear in the next 25 years. Continued loss of glacial ice is projected to lead to a shift in seasonal flow in many glacial catchments (Jiménez Cisneros *et al.*, 2014). Peak discharges are projected to occur in spring, whereas reductions in summer discharges are likely (Sorg *et al.*, 2012).

2.2.1.3 Runoff, River Flows and Water Stress

Projected changes in precipitation will lead to changes to runoff, river flows and water scarcity across the world. A comparison of 12 global climate models (GCMs) by Milly *et al.* (2005) showed that there are regional variations in runoff projections. While eastern Africa and Eurasia are likely to experience increases in runoff, of 10-40%, areas such as mid-latitude North America, the Middle East and southern Africa could see decreases in runoff of up to 30%. This shows that future changes in precipitation and runoff will be highly spatially variable and that changes in some regions may not be projected well by current models. Schewe *et al.* (2014) found a similar regional pattern of projected changes in runoff and river flow. However, they also noted the large spread of projections between different climate and hydrological models in some areas of the world such as northern Africa.

As the number of intense rainfall events increases, the likelihood of flooding also increases (Githui *et al.*, 2009). Betts *et al.* (2018) found that, with both 1.5°C and 2°C of warming, flooding events across the world increase in length in all models. By contrast, the reduction in moderate precipitation events could lead to increased water stress in countries with dry seasons. Gosling and Arnell (2016) found that more people are likely to experience higher water stress as a result of climate change than a reduction in water stress. Paltsev *et al.* (2016) found that the largest relative changes in water stress occur in Africa. They found that globally, at least 1 billion additional people are projected to experience at least moderately stressed water conditions worldwide by the end of the century.

There is already evidence of earlier spring snowmelt occurring in alpine regions (Laternser and Schneebeli, 2003). The projected precipitation shift from snowfall to rain may severely alter the winter flood regimes of mountain catchments, reducing the chance of snowmelt floods but increasing the possibility of very high river winter flows, or even flash floods. Berghuijs *et al.* (2014) found that shifts from snow to rainfall could lead to reductions in streamflow across catchments in the United States.

2.2.1.4 Groundwater

Potential impacts on groundwater recharge have not been investigated to the same extent as impacts on surface water resources (Kundzewicz and Doll, 2009). Groundwater is often more protected from seasonal variations and pollution than surface waters, making it an important resource in less developed countries. Although groundwater is already a vital resource for many countries, its importance is likely to increase in the future, as surface water quantity and quality alters. Modelling results suggest that some areas of the world, including parts of China and the USA, are projected to experience increases in groundwater by 2050, whereas other areas, such as the Mediterranean and southwestern Africa, are projected to see decreases (Kundzewicz and Doll, 2009). Despite uncertainty in the magnitude of groundwater changes, model results have clearly shown that sizeable alterations to available groundwater resources will be observed. Portmann *et al.* (2013) also investigated the impacts of climate change on renewable global groundwater resources, using five GCMs in the hydrological model 'WaterGAP'. Despite some variation between models, the results suggested that South America and the Mediterranean are likely to experience decreases in groundwater recharge, whereas western regions of North America could see increases in groundwater.

2.2.1.5 Water Quality

Rising temperatures will affect the rate of chemical and biological processes within aquatic systems (Jiménez Cisneros *et al.*, 2014). Furthermore, lakes and slow-flowing freshwater bodies may experience algal blooms as a result of stagnant water; which will be of particular concern for areas that are projected to experience a decrease in precipitation (Whitehead *et al.*, 2009). Algal blooms can block light and reduce dissolved oxygen concentrations, negatively impacting aquatic life. Increased volumes of suspended solids in the water column, occurring as a result of projected higher runoff volumes, would reduce the quality of the river water (Grayson *et al.*, 1997). Fine sediment may smother the substrate, depriving benthic organisms of light and oxygen. Projected changes to water quality will impact drinking water (Jiménez Cisneros *et al.*, 2014).

2.2.1.6 Soil Erosion and Sediment

Higher rainfall and increased runoff are likely to result in higher soil erosion. Even in areas of the world which are not projected to experience increases in average rainfall, soil erosion may increase as a result of more intense rainfall events. Extreme events have been projected to account for around half of the total soil erosion in semi-arid regions of Australia, Africa and Spain (Yang *et al.*, 2003, Bussi *et al.*, 2013). In addition, Knutson *et al.* (2010) found that projected increases in cyclones in the tropics could result in more frequent landslides and greater soil erosion. Greater soil erosion will lead to higher sediment loads in river systems (Whitehead *et al.*, 2009). However, the projections of changes to soil erosion occurring as a result of climate change are still very uncertain (Jiménez Cisneros *et al.*, 2014).

Therefore, global climate change is likely to have a range of impacts on both the quality and quantity of water, which will affect the whole hydrological cycle.

2.2.2 Biodiversity

There is growing recognition of the importance of climate change in determining changes to global biodiversity (Fischlin *et al.*, 2007, Post, 2013). Malcolm *et al.* (2006) go so far as to argue that climate change is the largest threat to biodiversity because it can affect all areas of the world, even areas far from human activity. Many species are already affected (Cramer *et al.*, 2014). If global temperatures were to reach 2°C above pre-industrial levels, 20-30% of species would be at risk of extinction (IPCC, 2007). Foden *et al.* (2013) conducted a trait-based assessment of birds, amphibians and corals and found that large proportions were highly vulnerable to 2°C of warming. Likewise, Warren *et al.* (2013b) analysed around 50,000 species and found that around 57% of plants and 34% of animals are projected to lose over half their climatic range if temperatures reach 3.6 °C above pre-industrial levels. However, sizeable losses have been projected to occur with values of warming below 2°C, especially in biodiversity hotspots (Warren *et al.*, 2011). Warren *et al.* (2018b) found that insects are particularly negatively affected by climate change, which will affect plant-pollinator interactions and likely have greater effects on entire ecosystems.

As well as rising temperatures, other climatic factors will lead to impacts on biodiversity. Rainfall volume and seasonality, sea level rise and changes to disturbance regimes are also important to consider. The impacts of these on biodiversity are outlined below. It is important to note that many species will be affected by a range of threats that result from climate change. For instance, coastal species and ecosystems could be adversely affected by sea level rise, increased temperatures and extreme climatic events (ECEs) (Nicholls *et al.*, 2007). Significant losses of biodiversity diminishes an ecosystem's ability to absorb other changes without losing stability (Falkenmark and Rockström, 2004). Therefore, ecosystems could be pushed towards their tipping points. Biodiversity losses can also negatively impact ecosystem services, which in turn can threaten human wellbeing (Diaz *et al.*, 2006).

The Living Planet Index shows a decline in global biodiversity of 52% between 1970 and 2010 (McLellan *et al.*, 2014), demonstrating that biodiversity is already being adversely affected by human activities. Although some assessments of potential changes exist, there are still large uncertainties in how biodiversity may alter with climate change; for instance, because some potentially important processes are not represented well in models. Regardless of this uncertainty, awareness of possible impacts, which would create chances for swift mitigation strategies, is paramount if large losses are to be avoided (Warren *et al.*, 2013b).

2.2.2.1 Rising Temperatures and Changing Patterns of Precipitation

Rising temperatures will affect both terrestrial and aquatic species. Li *et al.* (2009) show that temperature rises are the predominant driver of climate-related habitat loss at high elevations. Fire frequency is also expected to increase in areas affected by disturbance regimes (Krawchuk *et al.*, 2009). Most areas are also projected to experience a lengthening of the wildfire season (Liu *et al.*, 2010). In addition, the impacts of temperature increases have already been seen in the oceans. One of the most publicised threats with rising ocean temperatures is coral reef bleaching, which is expected to increase further as temperatures continue to rise. Coral reef bleaching has already been shown to have increased in frequency, particularly during El Niño events. Coral bleaching not only affects biodiversity but also the people who depend on them for their livelihoods, such as through tourism, fishing and as a natural coastal protection (Hoegh-Guldberg, 1999), showing the interconnectedness of natural and human systems.

Changes to precipitation will also impact species, particularly in the tropics. Some areas could experience major changes in precipitation patterns, which may be linked to larger scale changes, such as alterations to the monsoon regime. Higher temperatures are likely to lead to increased demand for water – both for humans and natural ecosystems. This may lead to greater human-wildlife conflict and competition for resources. As stated by Chamaille-Jammes *et al.* (2013), few animal species can survive beyond a short number of days without water. Furthermore, decreases in precipitation are often linked to significant decreases in river discharge, which will impact the aquatic species which live in the river system through changes to water quality and quantity. Understanding changes to water resources as well as other climatic factors is necessary to reduce threats to biodiversity.

Extreme climatic events (ECEs) may affect some species more than changes to the average conditions (Berghuijs *et al.*, 2014). Droughts are a threat to vegetation, which will have knock-on effects on the rest of the ecosystem. Heatwaves can cause mortality among a range of species. Palmer *et al.* (2017) found that, during extreme years, population crashes are more common than population explosions. Orsenigo *et al.* (2014) examined the effects of ECEs on plants and found that the responses were individualistic, with different plants responding in different ways.

2.2.2.2 Sea Level Rise

Coastal ecosystems often have a high biodiversity and are among the most productive in the world, but are projected to be vulnerable to losses with rising sea levels. Furthermore, many coastal areas are important areas of economic activities such as tourism and fishing, so they are already under pressure. Finlayson *et al.* (2005) argue that coastal ecosystems are one of the most severely threatened systems worldwide. Sea level rise is also a threat due to larger storm surges. Mangrove ecosystems are particularly vulnerable. These ecosystems act as a natural buffer and protect the coast from storm surge events in tropical regions of the world. For island ecosystems, the increase sea level and coastal flooding is likely to reduce the size of coastal wetlands, which are often important biodiversity areas, especially birds (Sekercioglu *et al.*, 2012). Many island species are endemic and could face extinction as a result of climate change.

2.2.2.3 Species' Responses to a Changing Climate

Impacts are projected for both individual species and as ecosystem-wide responses. Root *et al.* (2003) correctly stated that biodiversity has been responding and adapting to changes in climate throughout history, but that species may be ill-equipped to deal with the rate of current warming. Many effects will have a time lag and therefore the impacts of existing changes may be seen in the future. However, there is scientific evidence that some species are already moving as a result of feeling the effects of climate change (Zhu *et al.*, 2012). For instance, species have been recorded as colonising new areas. Wilson *et al.* (2005) found that montane butterflies in Spain had moved uphill between 1967 and 2004.

Individual species, and even populations, are projected to have varying sensitivity to climate alterations and a varying ability to respond to them. The threat of climate change is particularly severe for endemic species, as they are less likely to be able to adapt to the changes (Thomas *et al.*, 2004). There is also little evidence available on the distribution and characteristics of many endemic species. Species that are able to adapt to climate change are likely to do so in a number of ways. The most widespread adaptation to climate change is likely to be shifting geographical range (Root *et al.*, 2003), which will be the focus of Chapter 5 of this investigation. Further possible changes are genetic changes and alterations to species' phenology (Walther *et al.*, 2002).

Parmesan (2006) argues that shifts in a species' range is likely to be the most common response to climate change. More species are likely to move to a new area than adapt to the one they currently occupy, with most favouring moves to higher latitudes or higher elevations. Moving to higher elevations reduces a species' range size and results in greater competition with other species that already inhabit these higher elevations. Mountain plant and animal species moving uphill will lead to a greater risk of extinction. Chen *et al.* (2011) argue that some species will not be able to alter their ranges fast enough to keep up with the current rate of warming. Species have differing abilities to shift their range. For instance, the majority of tree species are likely to shift at a slower pace as they are less mobile than animal species (Corlett and Westcott, 2013). However, Steinbauer *et al.* (2018) found an increase in plant diversity on mountain summits as a result of upward shifts in the ranges of some plants. The opportunities for species to move to other areas of suitable habitat and climate may be limited by external factors caused by human activities. The ability of a species to move successfully will be limited by land use changes and the existence of habitat corridors. Landscapes are becoming increasingly fragmented and many immobile species will not be able to colonise across these fragments (Chen *et al.*, 2011). In addition, species considered to be habitat specialists may be lost as a result of climate change.

Another possible response to a changing climate is a phenological response. Phenology refers to the timings of cyclical or seasonal biological phenomena, such as migrations, egg laying or flowering (Walther *et al.*, 2002). The majority of taxa exhibit some phenological response as many organisms require a certain amount of heat – or accumulated temperature – in order to develop from one stage of their life cycle to the next. There is substantial evidence that the timing of these seasonal activities is already changing as a result of recent warming, showing that climate change is already affecting species (Root *et al.,* 2003; Visser and Both, 2005). These changes include earlier flowering and a lengthening of the growing season in some plant species. As well as flowering or egg-laying, some species – mainly insects – can slow or speed up their development rate depending on climatic conditions.

Phenological changes are likely to be a widespread response among plants, as many long-lived plants will not be able to shift their ranges in time with the rate of warming. Changes to the timing of fruiting or flowering of plant species are likely to have effects for several other species in the ecosystem. For instance, the timing of fruit on trees will impact the species that depend on these food sources. This can lead to trophic de-coupling; a mismatch of predator-prey interactions (Van der Putten *et al.*, 2010). Spatial differences in phenological changes are likely, with variations in the rate of warming and other climatic variables. In temperate regions, the accumulated temperature is often the most important factor in determining the timing of seasonal phenomena, whereas in the tropics rainfall can be seen to be more significant (Reich, 1995).

Changes to the timings of environmental cues that cause these processes to occur can lead to larger changes in the ecosystem, especially where migratory birds are responsible for seed dispersal. However, making generalisations about the phenological response to climate change is difficult. Thackeray *et al.* (2016) demonstrate that, at a UK-wide scale, phenological climate sensitivity varies greatly between species. Other local, non-climatic factors are also important; such as resource availability and population structure. Visser and Both (2005) support this, arguing that changes cannot be fully understood without examining the wider ecosystem in which the species lives and how that ecosystem is responding to climate change.

A further response to climate change is genetic or evolutionary alternations. Individuals and populations may differ in their ability to cope with rising temperatures. Those that are able to survive warmer conditions are more likely to breed and pass on these characteristics. Therefore, over time, evolutionary changes in a species are likely to occur. This is also linked to shifting species ranges, as changes in distribution of species impact genetic diversity. This is evidenced by the fact that the highest genetic diversity is seen in areas where species have persisted for an extremely long time and have survived previous climatic shifts in refugia (Falkenmark and Rockström, 2004). Species that cannot shift their range or have no new areas to colonise may experience inbreeding and a reduction in genetic variation.

If species are not able to respond to the changes in climate, they risk extinction. However, projections of extinction risks vary greatly across studies. Urban (2015) collated the existing literature and concluded that the highest extinction risks are projected for South America, Australia, and New Zealand. By contrast, the lowest extinction risks were projected for North America and Europe. Thomas *et al.* (2004) projected that between 15 and 37% of species could be committed to extinction by the 2050s under mid-range warming scenarios. Extinction risks are projected to increase with higher degrees of warming (Urban, 2015).

2.2.3 Agriculture

Agriculture and fisheries are highly dependent on the climate. Agriculture dominates over a third of the global land surface and is believed to remain the primary cause of biodiversity loss throughout the 21st century (Sala *et al.*, 2000). The agricultural sector is also the largest consumer of water (Van der Esch *et al.*, 2017). However, agriculture is also cited as the major mechanism for reducing poverty (Wheeler and von Braun, 2013), and so ensuring it can withstand future changes in climate is extremely important. The World Development Report 2008 (World Bank, 2007) identifies five ways climate change is projected to affect agricultural productivity: changes in temperature, changes in precipitation, changes in CO_2 fertilisation, changes to surface runoff and increased variability in weather.

It has been estimated that the demand for food and other agricultural commodities will become 3-4 times larger by the middle of the century (Tilman *et al.*, 2002). This increasing demand for food is likely to lead to competition for land. However, future changes to agriculture and other land uses are very uncertain as it depends on several factors, such as population growth, trade and economics. For much of the globe, agricultural expansion will only be able to occur on less productive land as the most suitable is already cultivated. In some regions, such as Japan and Northern Africa, there is little land left for cultivation (Mandryk *et al.*, 2015) as most of the land suitable for agriculture has already been converted.

As well as contributing to the warming, agriculture will be an important aspect of the solution (Reay *et al.*, 2012). Agriculture has the potential for carbon sequestration and increasing soil carbon in agricultural systems will be an important way of using soils as a carbon sink. Several agricultural management strategies can sequester carbon. The most widely known example is reforestation and afforestation. Additionally, choosing management practices that reduce carbon losses and adding carbon-rich matter to soils would reduce the impact of the agricultural sector. No-till systems, where the need for tillage equipment is eliminated, have the potential to increase soil carbon rapidly (West and Post, 2002). Some of these methods are likely to have co-benefits for the agricultural system itself, but all methods have trade-offs associated with them.

2.2.3.1 Impacts on Crops

Impacts of climate change on crop yields are particularly hard to assess (Challinor *et al.*, 2009a). This is partially because the variables that influence crop production are both biophysical and socioeconomic and partially because many studies are conducted at local scales. Climate change is a threat to crops both directly, through ECEs, and indirectly as a result of changes to freshwater resources, rising sea levels and pests and diseases (Porter *et al.*, 2014). Many crops are projected to be extremely vulnerable to climate change as high productivity relies on specific environmental conditions. Globally, the amount of cropland has remained relatively stable over recent years (Ramankutty *et al.*, 2008), as there are no large areas of land free to convert to agriculture. Instead, advances generally come from improved efficiency and more intensive use of the land. Irrigated agriculture only accounts for a small proportion of cropland (around 17% worldwide) but it provides around 40% of global crop production (Van der Esch *et al.*, 2017). Climate change is projected to affect the productivity in existing croplands and the potential for expansion (de Vrese *et al.*, 2018). Schleussner *et al.* (2018) found that reductions in future crop yields are likely even with only 1.5°C of warming. With 2°C of warming, tropical areas are likely to see more extreme low yields.

Climate change will likely benefit some crops, as these are projected to prefer the warmer conditions. Others are projected to suffer from decreased yields as conditions pass their optimum temperatures. Thornton *et al.* (2011) show that climate change is projected to reduce the length of the growing season for many crops. Studies have already found negative responses of wheat, maize and barley yields with increased temperatures (Lobell and Field, 2007). Plants will also be affected by the increase in carbon dioxide, which may enhance the photosynthesis rate while reducing stomata transpiration (Myers *et al.*, 2014). C3 crops, such as wheat, rice and soybean, are likely to benefit from increased CO_2, while C4 crops like maize, sugarcane and millet, are unlikely to experience much difference in yields as a result (Conway *et al.*, 2009). However, for the benefits of increased CO_2 to be exploited, other conditions (such as water availability and soil moisture) must also be present. Conversely, higher CO_2 has also been linked to reduced protein content in cereal plants, reducing the overall quality of the crop (Zhu *et al.*, 2018). This direct effect of elevated CO_2 on a crop's nutritional value represents a threat to human health.

Many studies have examined the potential impacts of climate change on wine production (Jones *et al.*, 2005; Jones *et al.*, 2010; Moriondo *et al.*, 2013). Many wine-growing regions are projected to experience a reduction in suitability in a changing climate (Hannah *et al.*, 2013). Jones *et al.* (2005) found that many wine-growing regions of Europe are already experiencing temperatures close to their optimum growing season temperatures. Further increases in temperature are likely to reduce the quality and yields in the region. Similarly, a substantial volume of research has been conducted on the projected effects of climate change on tea and coffee crops (Craparo *et al.*, 2015; Laderach *et al.*, 2017). Ramirez-Villegas *et al.* (2012) found that projected higher temperatures will necessitate the migration of Colombian coffee crops towards higher altitudes (to the relatively lower temperatures). Bunn *et al.* (2015) compared current suitable land for coffee production across the world with projected future suitability. Results showed that most coffee-growing regions will experience a reduction in suitability in the future. A similar situation has been projected for tea production across the world (Dutta, 2014; Gunathilaka *et al.*, 2017; Biggs *et al.*, 2018).

It is also important to note that climate change is projected to impact different agricultural systems in different ways and changes will be region-, and in many cases, site-specific. Several studies have already noted geographic variations in crop response to climate change (such as Deryng *et al.* (2014); Rosenzweig *et al.* (2014)). Paltsev *et al.* (2016) found that Africa and Latin America are likely to see increases in crop areas, while in North America, Europe and Southeast Asia crop areas are projected to decrease.

Projected changes to ECEs will also threaten crop production. The magnitude, timing and frequency of ECEs are all important considerations. Crops are particularly sensitive to droughts during the developmental stages (Trnka *et al.*, 2010). Droughts also affect soils which further impacts crop production. Li *et al.* (2009) found that global cropland drought-disaster risk would double by the end of the century, with maize- and sorghum-based agriculture most sensitive. Extreme weather in 2010 caused losses to Russia's wheat, as a result of extreme heat, and Canada's cereal harvests, as a result of heavy rains (Hayes *et al.*, 2011). Arnell *et* *al.* (2018) found that limiting global temperature rise to 1.5°C, could significantly reduce the proportion of global cropland exposed to drought.

2.2.3.2 Impacts on Livestock

Pastoral farming is another important element of global agricultural production. Livestock contribute directly and indirectly to increased atmospheric CO_2. Grazing reduces plant growth and can lead to carbon losses from the system if areas are overgrazed. By contrast, grazing can stimulate plant (herb) growth if the area is not too intensively grazed by livestock. Pastoral farming is likely to be affected by climate change in a number of ways. Droughts and heatwaves could increase livestock mortality, both by threatening food supplies and by heat stress (Mader and Gaughan, 2011). Heat stress in livestock can lead to increased vulnerability to disease, reduced fertility and reduced milk production. Furthermore, reductions in water resources that are projected for some regions will limit the volume of water available for livestock at the same time as higher temperatures cause livestock to increase their water intake (Kreikemeier and Mader, 2004).

2.2.3.3 Impacts on Fisheries

The ranges of many fish and shellfish species may change with alterations to the climate. These range shifts may lead to more competition for resources in some areas or a decline in fisheries in other areas. Changes in temperature can also affect the timing of reproduction and migration. Furthermore, marine disease outbreaks could increase with climate change. Ocean acidification will also have impacts on fisheries. Coral bleaching, which was described in Section 2.2.1, can impact fisheries. McClanahan *et al.* (2001) noted that corals can change composition after bleaching events and those which are able to survive often take a long time (months) to recover. Cinner *et al.* (2015) concluded that impacts on fisheries vary with temperature and the social dimensions of vulnerability of the people depending on them.

2.2.4 Multisectoral Impacts and Interactions

As stated in Chapter 1, the impacts of climate change on one sector are unlikely to be confined to that sector, but instead have consequences for other sectors or regions either directly or indirectly (Nicholls and Kebede, 2012; Toth *et al.*, 2003). These cross-sectoral impacts have experienced less research interest when compared to single sector effects and are therefore more poorly understood. However, it is increasingly understood that impact and adaptation studies should move away from sectoral studies and consider the interactions between sectors (Harrison *et al.*, 2015). Some studies have assessed cross-sectoral impacts of climate change at the global or continental scale, including Arnell *et al.* (2013), Piontek *et al.* (2014) and Warszawski *et al.* (2014). Baettig *et al.* (2007) created a climate change index for a global scale analysis. This index was a measure of how much climate will change relative to the current natural variability in different areas of the world. Byers *et al.* (2018) conducted a multi-sectoral study of the global water, energy and land impacts of climate change. Their results showed that India and Southeast Asia were projected to have the highest multi-sectoral risks. Impacts to the energy sector are projected to be particularly high across Africa.

Diffenbaugh *et al.* (2008) aggregated climate change impacts to identify climate change hotspots across the USA. They used the CMIP3 climate models to aggregate positive and negative changes in climate variables. Diffenbaugh and Giorgi (2012) extended this type of analysis to a global scale study using the CMIP5 models with the RCP4.5 and RCP8.5 pathways. These studies examined changes to climatic variables only and did not directly consider other sectors such as energy or agriculture.

Other regional-scale studies on cross-sectoral impacts of climate change have focused on Europe and China. The CLIMSAVE project (Harrison *et al.*, 2015) considered cross-sectoral climate change issues and adaptation across Europe. CLIMSAVE considered six key indicators of change (one per sector) which were chosen based on their representativeness of the sector and their relevance to the decision-makers. These indicators were artificial surfaces, people flooded in a 1 in 100 year flood event, timber production, land use diversity, the water exploitation index and the biodiversity vulnerability index. As part of this project, Dunford *et al.* (2015) assessed vulnerability to climate change across Europe. Their results highlighted the interactions between the different indicators and sectors. In addition, Berry *et al.* (2015) examined cross-sectoral interactions between different climate change adaptation and mitigation measures; identifying synergies and conflicts between the two. The authors found positive, negative and neutral interactions between adaptation and mitigation measures across Europe.

2.3. Climate Change in East Africa

This section will review the state of knowledge of climate change impacts on water resources, agriculture and biodiversity in East Africa.

2.3.1 Temperature and Precipitation

Many studies conclude that temperatures across Africa are projected to increase faster than the global average (Joshi *et al.*, 2011; James and Washington, 2013). Projections of changes to precipitation in East Africa are more uncertain than projections of temperature changes (Rowell, 2012). Alterations to precipitation across East Africa are likely to be extremely complex, with significant seasonal and spatial variations (Orlowsky and Seneviratne, 2012). de Wit and Stankiewicz (2006) show that large parts of East Africa may experience an increase in annual average rainfall with climate change. Hulme *et al.* (2001) and Dessu and Melesse (2013) further this argument, suggesting that in general, precipitation across East Africa is likely to increase between December and February. By contrast, Patricola and Cook (2010) projected lower rainfall across much of East Africa for August and September.

Adhikari *et al.* (2016) compared the results of previous projections of precipitation change for the East African countries. They found that increases in precipitation are projected for Ethiopia, Kenya, Tanzania, Uganda and Rwanda by the 2090s. By contrast, no substantial changes to rainfall were projected for Malawi, Mozambique or Zambia. However, substantial uncertainty in the projections, due to the different emissions scenarios and climate models, was also apparent. There are still large uncertainties in GCM projections of large-scale precipitation changes across Africa (Hulme *et al.*, 2001). In East Africa, rain can occur in isolated patches or broad bands (Douglas *et al.*, 2008). Rain falling in discrete patches would be more difficult to project using large-scale climate models.

2.3.2 Water Resources

Climate change is projected to bring elevated levels of runoff in some countries of East Africa. Runoff is a particularly important part of understanding water resources, as it will be affected by both changes in temperature (through evapotranspiration) and precipitation. Areas that experience increases in runoff during the rainy seasons may not also experience a reduction in water shortages (Githui *et al.*, 2009). Instead, as these increases in runoff only occur over short time periods (from rainfall in single storms), they are more likely to lead to flooding. Milly *et al.* (2005) compared the results of 12 different climate models and found that runoff in eastern African is likely to increase by between 10 and 40%.

As precipitation and runoff evolve, so will the volume and timing of water entering and travelling through the river network. Arnell (1999) used the HadCM3 model to examine changes in water resources with climate change. Results showed that across East Africa, high flows are likely to increase whereas low flows are projected to decrease significantly by the 2050s. This conclusion is supported by the smaller-scale research of Githui *et al.* (2009), who modelled future flows in the Nzoia River Basin, Kenya. High flows were projected to increase in the future, with greater increases in the 2050 period. However, there was also greater uncertainty between the different models in the 2050 period than the 2020s. The highest increases in baseflows were seen in the December to February rainy season. Dessu and Melesse (2013) have shown similar results, using the SWAT model to show that river flows in the Mara River Basin (Kenya/Tanzania) in the wet seasons are likely to increase but little change is projected for the dry seasons. Mati *et al.* (2008) also examined the Mara River, finding evidence that high flow incidents are increasing in frequency and occurring earlier in the season. Kim and Kaluarachchi (2009) projected changes in annual runoff of between -25 and +32% for the Upper Nile basin by the 2050s. This shows that there is a significant amount of uncertainty in the projections for this area. These studies show that there is a large amount of spatial variability in projected changes, suggesting both increases and decreases in flows could occur in the East African region.

2.3.3 Agricultural Change

Research into the potential impacts of climate change on agriculture in East Africa is less developed than global scale research. Overall, climate change is expected to reduce crop yields in Africa due to shorter growing sessions, increased occurrence of pests and diseases and increased water stress (Niang *et al.*, 2014). Adhikari *et al.* (2015) reviewed previous studies on the potential impacts of climate change on fourteen staple and cash crops in eastern Africa. They found substantial reductions in yields, with wheat the most vulnerable of the crops. Thornton *et al.* (2009) found considerable spatial and temporal variation in crop response across the East African region. Mountainous areas may experience increases in crop yields, whereas lowland areas are more likely to see reductions in yields. In the past, the relatively lower temperatures limited crop yields at higher elevations, but as the climate changes, these areas may become more suitable for crop growth. There are large uncertainties in the response of some crops (Lobell *et al.*, 2008). Lobell *et al.* (2008) used 20 GCMs with statistical crop models for the

2030s across food-insecure regions of the world. For East Africa, models projected decreases in production for cowpea, beans, sugarcane, with cowpea the most negatively affected. Contrastingly, increases in production were projected for wheat. Lobell *et al.* (2008) found that the models disagreed on the sign of the change in production for maize and sorghum. As maize is the most widely cultivated crop in sub-Saharan Africa (Smale *et al.*, 2011), there is a significant volume of research into how it may be affected by climate change. Most studies conclude that maize will be negatively affected (Lobell and Field, 2007; Nelson *et al.*, 2009). Similarly, sorghum is an important crop in East Africa as it is able to grow in a wide range of temperatures and rainfall patterns (Wortmann *et al.*, 2009). Previous studies have shown that sorghum is likely to be more resilient to changes in climate than maize, but that reductions in yields are still possible (Liu *et al.*, 2008; Nelson *et al.*, 2009; Knox *et al.*, 2012).

Some studies focus on high value crops. Jaramillo *et al.* (2011) found that the coffee berry borer (*Hypothenemus hampei*) was already benefiting from higher temperatures and could significantly impact coffee production in East Africa. The negative effects of climate change on *Coffea arabica* yields in East Africa was also noted by Craparo *et al.* (2015), who focused on the Tanzanian highlands. Areas suitable for both tea and coffee production are expected to shift towards higher altitudes (Adhikari *et al.*, 2015).

2.3.4 Biodiversity Loss

Research into biodiversity change on the regional scale for Africa is limited, as studies tend to focus on smaller regions or single ecosystems within the individual countries. However, East Africa is identified as an area of concern in some global-scale analyses (Foden *et al.*, 2013). Research has also shown that a large proportion of East African species are already facing threats. The IPBES (2018) shows that nearly 40% of species endemic to East Africa are classed as ‘vulnerable’ or higher risk (i.e. endangered, critically endangered, extinct in the wild or extinct) by the IUCN Red List. This is the highest proportion for any region of Africa.

2.3.5 The Importance of Extreme Climatic Events

ECEs produce a disproportionately large volume of climate-related damages, although many impact assessments focus on the mean change in climate (Katz and Brown, 1992; Seneviratne *et al.*, 2012). Flooding is a regular occurrence in many parts of East Africa, with the two wet seasons often leading to biannual flooding along many major rivers. Haile *et al.* (2013) examined damage from flooding in Ethiopia and found that although large floods occurred several times in the last decade, the most damage was done by the 2007 inundation, where heavy rainfall extended for around 8 weeks. As urban populations continue to expand and anthropogenic impacts on the land and drainage intensify, the risk of flooding in East African towns and cities increases (Douglas *et al.*, 2008). However, as Whitfield (2012) correctly notes, detecting changes in flood regimes that are due to anthropogenic climate change is extremely difficult as natural variability is also important.

Studies of droughts in East Africa are fairly limited in comparison (Hastenrath *et al.*, 2007), but research has shown that historically drought-prone regions are likely to experience a greater risk in the future (Fu and Feng, 2014; Prudhomme *et al.*, 2014; Lehner *et al.*, 2017). Droughts can be broadly classified into three categories: meteorological drought, agricultural drought and hydrological drought. Droughts can affect both surface and groundwater resources, and therefore need to be carefully considered when discussing water resources management. 9 out of the top 10 disasters in Kenya from 1900 to 2018 in terms of total number affected have been droughts (EM-DAT, 2018). 4 of these droughts have occurred in the last 10 years. By contrast, floods cause more economic damage. A similar situation is seen for Tanzania and Uganda, with the majority of top 10 disasters in terms of numbers affected being either a flood or drought (EM-DAT, 2018). Once again, the floods caused more economic damage.

Extreme heat is also projected to affect African countries in the future. Russo *et al.* (2016) found that many African countries are projected to experience regular heat waves by the 2040s. Similarly, Weber *et al.* (2018) found that longer and more frequent heat waves are likely even if the global mean temperature rise remains below 2°C. Heat waves will have indirect impacts on multiple sectors, including human health and agriculture.

Furthermore, as well as understanding the changes in ECE occurrence, it is necessary to understand the vulnerability of the local people. Adger *et al.* (2003) showed that the populations of developing countries have traditionally been the most resilient to both droughts and floods. However, Dai (2011) argues that African farmers are very limited in how they can respond to droughts. Therefore, if

ECEs do increase in magnitude and frequency in the future, East Africans may be unable to effectively deal with the consequences.

2.4 Processes Leading to Short Term Climatic Variations in East Africa

It is important to consider longer-term climate change caused by increasing concentrations of greenhouse gases in the atmosphere in the context of smaller scale, natural climatic variations. Studies have determined that the impacts of climate variability are more significant to crop production than changes to the mean conditions (Katz and Brown, 1992; Seneviratne *et al.*, 2012; Ray *et al.*, 2015).

Douglas *et al.* (2008) examined rainfall records to show that there is a large amount of annual and decadal variability in East Africa. Several processes are important for creating short term variability in East African climates and year-on-year variations can be significant (Frederick and Major, 1997). Variations in natural forcing factors, such as the Earth’s Orbit and the volumes of solar radiation, can cause short term variations in climate (Sheffield and Wood, 2008). The importance of understanding these short-term climate variations is noted by Hulme *et al.* (2001), who go so far as to argue that understanding these phenomena is the greatest challenge facing Africa-focused climate scientists. It is important to consider climate variability when examining climate change because the effects of natural variability could be exaggerated by the anthropogenic warming. In addition, the climate naturally varies on timescales which are important for water resource managers to understand (Omondi *et al.*, 2013).

One of the most important factors in determining East African climates is the Indian Ocean Dipole (IOD). The Indian Ocean Dipole represents the total of the sea surface temperature (SST) variations that arise in the tropical Indian Ocean (Marchant *et al.*, 2007). As scientists are still working to fully understand this phenomenon, the IOD is, as yet, not well represented in global circulation models. The IOD is extremely important in influencing the East African climate between March and May, during the long rains (Gadain *et al.*, 2006). The El Niño Southern Oscillation (ENSO) is another oceanographic phenomenon which affects the East African climate (Hulme *et al.*, 2001). However, despite widespread research showing ENSO is associated with short rains, there is no consensus about the extent of the ENSO influence on East African climate. Bahaga *et al.* (2015) concluded that the IOD is the main driver and that ENSO has a minor influence.

The Inter-Tropical Convergence Zone (ITCZ) is also important in affecting seasonality, with its annual migration leading to the seasons (monsoons). The long rainy season, between April and June, is associated with the slow northwards movement of the ITCZ, whereas the short rains are linked to the more rapid southerly transition (Bahaga *et al.*, 2015). However, Marchant *et al.* (2007) argue that although it is important to consider the effects of the ITCZ on East African climates, the ITCZ must be considered as the sum of several smaller-scale systems. Therefore, it is important to note that the processes influencing climate and its associated impacts work on a range of spatial and temporal scales. Omondi *et al.* (2013) rightly show that the decadal variability in the three different oceans associated with East African climate variations all interact and even when one is dominant, the others are also influential.

2.5 Non-Climatic Factors affecting Biodiversity, Agriculture and Water Resources

Anthropogenic climate change is just one of the stressors affecting global biodiversity, agriculture and water resources. Climate change will interact with these other stresses and therefore they must be considered in conjunction, rather than as acting in isolation (Root *et al.*, 2003). This section will present the main human-induced stresses that need to be considered alongside global climate change.

2.5.1 Population Growth and Urbanisation

Although climate change will be a key driver for many changes to future water supply and demand and potential biodiversity losses, there are other factors which will be influential. Firstly, population change will alter future water demand. Frederick and Major (1997) argued that, in the future, population growth will be the most important factor in determining the availability of water in the developing world. Vorosmarty *et al.* (2000) support this, arguing that population changes and economic development will be more important than climate change for water availability. World population is expected to continue to grow, with much of this growth in developing countries, in particular in urban areas. Increasing the number of people relying on limited water resources will lead to additional pressure on sustainable management strategies. Flörke *et al.* (2018) found that global urban water demand could increase by around 80% by 2050 and that one in six large cities is likely to be at risk of water deficits. As countries develop, more people tend to move to urban areas in search of better living conditions and economic opportunities. The size of the urban population in East African countries is likely to continue to increase in the future, placing more pressure on limited water resources (Douglas *et al.*, 2008). Therefore, demographic change must be considered in conjunction with climate change when examining the future of natural systems.

2.5.2 Land Use Change and Degradation

Land use and cover is constantly changing across the entire world, as a result of multiple drivers and impacts, which can contribute to climate change and biodiversity loss (Houghton *et al.*, 2012; Willcock *et al.*, 2016). The greatest global change in land use has been towards more agricultural land. Krausmann *et al.* (2013) estimate around one third of the terrestrial land surface is dedicated to agriculture. In addition to agriculture, other demands on land, such as urbanisation and bioenergy, are expected to increase in the future (Van der Esch *et al.*, 2017).

Land degradation is extremely difficult to quantify. Van der Esch *et al.* (2017) argued that the degree to which land use practices, particularly agricultural practices, degrade land is very uncertain.

Romanowicz and Booij (2011) argue that one of the biggest challenges in current hydrological research is assessing whether changes to water availability are caused by climate change or land use change. Models are used to assess the impacts of historical and projected future land use changes as well as changes in climate (Thanapakpawin *et al.*, 2007; Huisman *et al.*, 2009). Some previous studies have found that combining land use and climate changes can lead to the two effects cancelling one another out (Yan *et al.*, 2016; Zhang *et al.*, 2016). However, Hejazi and Moglen (2008) argued that the combination of land use and climate changes might result in more substantial hydrological changes than either driver alone. This demonstrates the complexity of climate and land use changes. Therefore, the combination of effects of land use and climate change is still an important topic of research.

2.5.3 Habitat Fragmentation and the need for Wildlife Corridors for Biodiversity Protection

Habitats are becoming increasingly fragmented as a result of human development. As settlements and agriculture expand, more land is converted from its natural vegetation. In addition, road and rail networks cut across the landscape, splitting areas of similar vegetation into smaller fragments. Increasingly fragmented habitats will limit species' abilities to respond to climate change by migrating. Although many species are likely to need to shift their range to respond to climate change, increasingly isolated fragments of suitable habitats will make movement more difficult for many species. Wieczkowski (2010) argues that species that remain in isolated habitat fragments will begin to experience other negative effects, including a reduction in natural genetic variation within the population and even local extinctions.

Preserving wildlife corridors can facilitate species movement across the landscape. Wildlife corridors are defined as narrow strips that link at least two larger habitat patches. Jones *et al.* (2009) also show the importance of maintaining connectivity within landscapes, particularly between conservation areas, for reducing pressure on ecosystems and encouraging demographic links and gene flow. However, detailed knowledge of important wildlife corridors in many countries is still lacking. Perre *et al.* (2014) highlight the knowledge gap on wildlife corridors in Africa, showing that those which have been identified have focused on large species.

2.5.4 Invasive Species, Weeds, Pests and Diseases

Invasive species are non-native plants or animals that have been introduced to environments and are causing harm to the existing ecosystem. Biodiversity and agricultural systems are impacted by invasive species, which may increase the vulnerability of these systems to climate change. Roy *et al.* (2017) shows that one quarter of the world's most invasive species have environmental impacts that have been connected to diseases in other wildlife. Oerke (2006) found weeds caused more damage than pests and diseases, but that the total losses vary between crops. Porter *et al.* (2014) note that the effects of CO_2 fertilisation that are projected to benefit crop production will likely also benefit invasive weeds. In addition, warmer winters and the earlier onset of spring could allow some parasites to survive more easily. A shift in climate could lead to pathogens and diseases moving into new areas. These negative impacts on agricultural systems could also lead to threats to human health.

2.5.5 Impacts of Policy

Policy and management practices will have a significant impact on water resources biodiversity and agriculture in the future. In recent years, the volume of climate change relevant policies and legislation has increased dramatically. At the national and international levels, there are several important climate policies and targets. The Sustainable Development Goals (SDGs) are 17 global social and economic development goals set by the United Nations. These goals replaced the Millennium Development Goals which ended in 2015 and are statements of ambitions rather than legal obligations. SDG13 aims specifically to combat climate change, but there are also other SDGs which are relevant to climate change action. SDG15, 'Life on Land', focuses on the sustainable use of ecosystems and protection of biodiversity and SDG14 covers marine species and coastal biodiversity. In addition, SDGs also relate to water (SDG6 on clean water and sanitation and SDG12 on the responsible consumption of natural resources) and agriculture (SDG2 on reducing hunger).

In 2015, the Paris Agreement was adopted at the United Nations Framework Convention on Climate Change (UNFCCC) in Paris twenty first Conference of the Parties (COP 21). This reaffirmed commitments to limiting global temperature rise to 2°C above pre-industrial levels and even potentially limiting to 1.5°C. In addition, the Paris Agreement calls for a reduction of net anthropogenic GHG emissions to zero during the second half of the century (Tanaka and O'Neill, 2018). The Paris Agreement requires each Party to prepare nationally determined contributions (NDCs). These NDCs include the national efforts that the country will take to reduce emissions and adapt to climate change. However, they currently fall short of the emissions reductions necessary to meet the temperature threshold targets (Rogelj *et al.*, 2016). The NDCs would currently lead to global temperature increases of between 2.7°C and 3.2°C (Rogelj *et al.*, 2016). The Paris Agreement is now recognised as a turning point in global efforts to deal with climate change. However, immediate mitigation action may be needed in order to meet the targets. Arnell *et al.* (2013) found that even if emissions had peaked in 2016, most effects of climate change, both positive and negative, at the global scale would not have been avoided by 2050s. Policies were found to delay the impacts but negative impacts would still occur.

The National adaptation programmes of action (NAPAs) were created by the Least Developed Countries (LDCs) to identify priorities for adapting to climate change. Similarly, Nationally Appropriate Mitigation Actions (NAMAs) were developed. In addition to climate change policies, there are a number of international agreements and conventions that focus on protecting biodiversity, which are also relevant to this work. The Convention on Biological Diversity, the Convention on

Conservation of Migratory Species and the Ramsar Convention on Wetlands aim to conserve the world's species and ecosystems.

2.6 The Kenyan Context

2.6.1 Demographic and Socio-economic Conditions

The World Bank (2016) estimated the population as around 48 million. Population is concentrated around the wetter areas (Rowntree, 1990) and high potential agricultural areas (Ongwenyi *et al.*, 1993). Many native peoples still have a close relationship with the land for their wellbeing and livelihoods and the majority of Kenya's population still live in rural areas. Kenya has extremely limited renewable water resources and many people still rely on untreated water for domestic uses. Baker *et al.* (2015, p.17) argued that Kenyans are 'living at the nexus of development and increased pressure on land and water resources'.

Many catchment areas in Kenya are being impacted by land degradation, due mainly to the expansion of agriculture. Water scarcity occurs across the country due to low rainfall, illegal and excessive water extraction, inappropriate land uses along rivers, weak policy enforcement and population pressures (Hoang *et al.*, 2014). Olang and Furst (2011) go so far as to argue that land use change induced by agricultural expansion is one of the most significant threats to the country's hydrology. This is of particular concern in the Mara River basin, southwestern Kenya, which was recently named the Seventh Wonder of the New World (Mati *et al.*, 2008). Land cover change and degradation not only diminishes resilience against drought but can also increase the speed and volume of surface runoff, reducing the time to peak river flows and increasing the risk of flooding (Mati *et al.*, 2008). These social and economic conditions are extremely important to consider when setting out management strategies for issues such as climate change and water resources management.

2.6.2 Policy Context

As poverty alleviation, principally through economic development, is the main driver of policies and targets (Kithiia, 2011), it is clear that mitigating or adapting to climate change may come into conflict with government initiatives. In addition to this, African governments which have made commitments to adapt to climate change, including Kenya, may be ill-equipped to manage the impacts (Kula *et al.*, 2013). As stated in Chapter 1, the GoK has identified climate change as a significant challenge to attaining Vision 2030. However, to date, there is little direct consideration of climate change in existing sectoral development plans. Indeed, several of the adaptation actions listed in Kenya's National Adaptation Plan (GoK, 2016) involve developing sectoral adaptation strategies within the next 1-5 years.

In 2017, the GoK (2017) launched the National Spatial Plan, 2015-2045. Its development was set out as a flagship project in the Vision 2030 and it is the government's first attempt at producing a comprehensive land plan (GoK, 2008). In the National Spatial Plan, the Government of Kenya acknowledges that previous plans have focused purely on economic development, rather than land planning and aims to ensure that in the future land is used in the optimum way. During the development of the National Spatial Plan (GoK, 2017), the GoK combined data on agro-ecological zones, development corridors, resource potential and population density. This information, along with consultations with experts, existing development plans and scenario analysis in relation to future population growth and urbanisation, were combined. The optimal land use for each area was determined by analysing these information sources.

Therefore, a full understanding of the impacts of climate change is necessary to aid in this process. Following on from this national-level document, each county will develop a County Spatial Plan. Although larger policy priorities are decided upon by the national government, the county governments are in control of many land issues. Kenya has 47 counties, 16 of which are covered all or in part by the Tana River Basin. These counties have already been shown in previous chapters. Much of the land in the Tana River Basin has been classified as land available for development expansion by the National Spatial Plan (GoK, 2017), including areas along the coast and near to the edges of PAs.

Kenya's wider development agenda, the Vision 2030 (GoK, 2007), also discusses land-related issues. The Vision sets out a number of flagship projects for the Tana River Basin, including increased irrigation of arid or semi-arid land to expand agriculture and the construction of a canal from the main river to the town of Garissa to provide water to residents. The Vision also states the intention to protect wildlife corridors, which are mapped in the Report on Wildlife Corridors and Dispersal Areas (Ojwang' *et al.*, 2017).

Kenya has completed its national climate change response strategy (NCCRS) (GoK, 2010b) and national climate change action plan (NCCAP) (GoK, 2012). The NCCRS provides the framework for integrating climate concerns into the development priorities and planning. The NCCAP summarises mitigation and adaptation options as well as recommended actions. Kenya also produced a national adaptation plan 2015-2030 (NAP; GoK, 2016), which details the country's vulnerability to climate change and the actions they will take to adapt to the effects. While the national government will lead the process, a key element of the NAP is to mainstream climate change adaptation into the county-level development plans. Adaptation measures are split by sector, although many actions are cross-sectoral. An example of this is the promotion of efficient irrigation systems, which is listed as an action for the water sector but also links to agriculture. The reforestation effort in the Upper Tana is given as an example of ongoing initiative to help support energy development. Continuing the rehabilitation of the water towers is seen as a long-term action to help ensure sustainable energy production (GoK, 2016). In terms of agriculture, the medium-term actions include water harvesting for crop production, conservation agriculture, integrated soil management, agro-forestry and use of drought-tolerant varieties of traditional high value crops. Other actions include the restoration of lands degraded by overgrazing by livestock and promotion of livelihood diversification.

One of the long-term actions put forward in the NAP is to update land use plans to include climate change scenarios and integrate climate change scenarios into spatial planning, showing that this has not been widely considered up until now. This supports Ongugo *et al.* (2014) argument that these existing policies and legislation are inadequate to combat and adapt to climate change. The importance of indigenous knowledge in adapting to climate variability is also acknowledged throughout.

As well as the Vision 2030, NAP and National Spatial Plan, there is a large range of other legislation which affects both climate change and land use policy and practice. Table 2-1 shows the policies and details relevant to this work. The targets include a range of environmental protection practices which encourage sustainable development. One important action, which is included in many different policies, is to increase the national forest cover. Various plans, including the National Forest Policy, promote planting of indigenous and exotic species. The Kenya Forestry Research Institute (KEFRI, 1990) compiled a list of suitable tree species for afforestation or reforestation projects. This list includes a range of species for ecosystem restoration, fuelwood and other uses.

The GoK produced a number of documents outlining water development and management policies. Major national development targets include increased energy generation and efficiency, improved access to water and sanitation, developments in irrigation systems allowing a greater area to be covered and sustainable and integrated management of water resources (MENR, 2013a). The 2002 Water Act introduced the idea of catchment-based management. Previously, the GoK had relied on management techniques that were split across administrative boundaries. With the Water Act, a new organisation, known as the Water Resources Management Authority, was established to oversee issues with water resources (MENR, 2013a). This change to catchment-scale management mirrors the shift in thinking across the European Union, which was introduced with the Water Framework Directive (WFD, 2010).

Table 2-1: Relevant policy documents

Policy	Land Use Component	Details
National Climate Change Response Strategy (GoK, 2010)	Climate smart agriculture	Integrating climate change adaptation and mitigation measures into all planning and development objectives
National Climate Change Action Plan, 2013-2017 (GoK, 2012)	Proposes strategies to cushion agricultural sector from climate variability and change.	Including drought-tolerant, high-value crops, water harvesting for crop production, conservation agriculture and integrated soil fertility management.
National Environment Policy (MENR, 2013)	Framework for an integrated approach to sustainable management of Kenya's environment and natural resources	Measures and actions needed to respond to key environmental issues and challenges, for each of the different ecosystems.
Kenya National Adaptation Plan (NAP) 2015-2030 (GoK, 2016)	Integrate climate change into development agendas at national and local levels Develop sectoral plans (e.g. for forestry, wildlife) with adaptation actions included.	Aims to ensure future adaptive capacity and long-term resilience of key economic sectors
National Forest Policy (MENR, 2014)	National forest cover target of 10% of land area	Reforestation and afforestation projects
Kenya Vision 2030 (GoK, 2007)	Rehabilitation of the Water Towers, move towards more commercially-orientated agriculture, increase forest cover	The Vision includes flagship projects for catchment management, land cover mapping and agricultural development.
National Spatial Plan, 2015-2045 (GoK, 2017)	To develop a national framework for the optimal use of land and resources	Allocates land based on agricultural suitability and potential for economic development.

Table 2-1

National Water Master Plan Towards 2030 (MENR, 2013)	Develop irrigation potential Water harvesting and storage	Proposes the development of irrigation programmes to encourage further agricultural development in the ASALs.
Agriculture Act, 2012	A compulsory farm tree cover of at least 10% of any agricultural land holding	Aiming to enhance conservation of water, soil and biodiversity.
Agricultural Sector Development Strategy (ASDS) 2010-2020 (GoK, 2010)	Sustainable land use practices and scaling up of technologies for drought-prone areas	The blueprint for the agricultural sector to implement the Vision 2030. Integration of tree crops into agricultural production, introduction of water-efficient crop species.
Wildlife Conservation and Management Act, 2013	Plans to identify and protect key areas for wildlife, including migratory routes and corridors.	Ecosystem-based conservation plans, identify priority areas for wildlife conservation, creation of community conservation areas.
Wildlife Corridors and Dispersal Areas report (Ojwang' et al., 2017)	Wildlife corridors identified.	To identify and protect important wildlife corridors and protected areas and ensure species are allowed to disperse.

2.7 Previous Research on the Tana River Basin

The Tana River Basin has previously attracted scientific interest, including studies on the impacts of dam construction, the ecological importance of the lower section of the basin as well as more recent investigations into the impacts of climate change on the hydrology of the area.

Human intervention across the Tana River Basin has been a popular research topic. Maingi and Marsh (2001; 2002) examined the hydrological impacts of dam construction in the upper reaches of the Tana River, which has already influenced the river system and wellbeing of indigenous groups. The construction of the Masinga and Kiambere Dams in the upper basin resulted in a reduction of river meandering, increase in channel depth and increases in precipitation. In addition, the construction of dams has negatively impacted the Malakote agriculturalists, by reducing the floodplain inundation and therefore soil nutrients on their land. Traditional land use practices of small scale agriculture, pastoralism and fishing have maintained the ecological balance of the lower Tana for thousands of years. Terer *et al.* (2004) researched the Pokomo and Wardei people, who have traditionally exploited and developed strong affinity to wetlands and their resources. The local people had vast knowledge on wetland ecosystems especially on their ecological changes such as flooding regime, decline in sizes and sedimentation.

In addition, ECEs have been the focus of previous research on the Tana River Basin. Hughes (1990) examined the impacts of flood regimes on forest distribution and growth along the lower Tana River. Analysis of the data showed that the average duration of the longest annual flood was 11 days or fewer, but flooding did not occur every year. The results suggested that the forests in the Tana Basin have extremely limited tolerance to alterations in flooding frequency and duration. Therefore, future changes in climate and flood regime threaten the existence of the Tana floodplain forests. Hughes (1990) also remarks on the lack of data, arguing that research on African floodplains is still in its infancy, due to poor hydrological records. This conclusion is supported by research on other Kenyan river catchments (Olang and Furst, 2011; Dessu and Melesse, 2012; Omondi *et al.*, 2013). Therefore, future research into these areas is extremely important. By contrast, Ngaina *et al.* (2014) found an increase in drought frequency and magnitude in Tana River County in the future, which could lead to food insecurity.

Several studies have focused on endangered primates in the basin. Andrews (1975) undertook a two-month survey of the ecology of the Lower Tana River basin, recording all of the species present in the area. Medley (1993) found that the Tana River red colobus and the crested mangabey are very susceptible to forest loss and fragmentation. Wieczkowski and Kinnaird (2008) studied the change in primate diets in response to changes in the forest composition of the Lower Tana. The tree species favoured by the endangered monkeys were Sage-leaved alangium (*Alangium salviilfolium*), Sycamore fig (*Ficus sycomorus),* Snuff-box tree (*Oncoba spinosa*), Wild date palm (*Phoenix reclinata*), jackalberry (*Diospyros mespiliformes*) and *Hyphaenae compressa*. The importance of *Ficus* species and the wild date palm was also noted by Medley (1993).

Smaller scale studies have focused on the ecology of individual protected areas within the basin (e.g. Okita-Ouma *et al.* (2016) on ecosystem connectivity in the Tsavo National Parks) or particular species of conservation concern (e.g. (Kimitei *et al.*, 2015)) on habitat suitability modelling for the Hirola).

More recently, Nakaegawa and Wachana (2012) conducted the first study assessing future hydrological change in the Tana River Basin as a whole, using a global hydrostatic Atmospheric Global Climate Model (AGCM) and a 0.5°–mesh global river-routing model. Four different hydro-climate variables were examined: precipitation, evaporation, total runoff and soil water storage. Nakaegawa and Wachana (2012) performed 25-year time-slice experiments for the present day and 21st Century climates and found average annual increases in precipitation of around 15%. Other studies have focused on the upper Tana River Basin. This focus appears to have been at least partially determined by data constraints. The SWAT model was applied to the Tana River Basin by Jacobs *et al.* (2007) to investigate land use changes in the upper Tana basin.

As the basin has been pinpointed as important for development, a number of environmental assessments have been undertaken. The IVM Institute for Environmental Studies conducted an assessment of ecosystem services provided by the Tana River Basin under current climate conditions (van Beukering and de Moel, 2015). Similarly, the IWMI produced a large report on the hydrology of the Tana River Basin with climate change as part of the WISE-UP to Climate project led by the UNEP. The baseline report on ecosystem services (Baker *et al.*, 2015) effectively collates the available data on geography, hydrology and ecosystem services within the basin. These data have since been compiled into a file geodatabase and online mapping tool (Hussain and Baker, 2016). The analysis of hydrological change conducted through this IWMI project was presented by Sood *et al.* (2017). Changes to four hydrological characteristics (water yield, groundwater recharge, baseflow and flow regulation) were projected for three future time periods. Results indicated increased water availability in the future but also showed that changes in the key hydrological properties were greater than the projected increases in rainfall.

2.8 Gaps in the existing literature

This literature review has highlighted several gaps in the current knowledge, where further research would be highly beneficial. Firstly, the relatively lower research attention paid to Africa over Europe and North America (Hulme *et al.*, 2001; Shongwe *et al.*, 2011), despite its known sensitivity to climate change, provides some support for the focus of this research. Niang *et al.* (2014) highlighted the relatively poor understanding of how climate change will impact upon water resources in Africa.

An important gap in the current knowledge of the potential impacts of climate change on the Tana River Basin, which this thesis addresses, is an analysis that considers a full range of climate change scenarios. Although studies assessing the impact of climate change on the water resources of the basin have been conducted (Nakaegawa and Wachana , 2012; Sood *et al.*, 2017), these have not considered the complete range of GCMs and emissions scenarios. These previous studies might not adequately represent the range of possible future conditions due to the limited number of GCMs employed. Therefore, the uncertainty cannot be fully appreciated. In addition, data constraints have led to previous work only focusing on the upper Tana basin, whereas this research will investigate the whole catchment. This research also employs a different hydrological model, so findings from this study build on previous work.

Some cross-sectoral analyses have been conducted on the hydrology and ecology of the basin (van Beukering and de Moel, 2015; Baker *et al.*, 2015), but these do not fully take into account the projected effects of climate change. There are still important gaps in the knowledge of how Tana River Basin ecosystems will respond to climate change. No other studies have considered how the climate envelop of species that occupy the Tana River Basin are projected to change. This study not only examines a wide range of species at the taxa level (for mammals, birds, reptiles, amphibians and plants) but also considers projected range shifts in individual, case study, species from the IUCN's Red List. Furthermore, this study is the first to consider the ability of some species within the basin to autonomously adapt to climate change by moving with their climate envelope (dispersal) and the potential barriers they may face while doing this, such as infrastructure or alterations to water resources as a result of the changing climate. In effect, this study addresses a major omission in many studies of species distribution changes across the world, which only focus on the direct impacts of climate change. This was acknowledged by Pacifici *et al.* (2015), who argued that the interactions between current threats to species and climate change are vital topics of research. Moreover, few studies have identified wildlife corridors connecting the protected areas in East Africa, despite this being an important way of preserving biodiversity. This void of current research was recently acknowledged by Perre *et al.* (2014). By considering the potential for species to disperse and track their preferred climate, this study identifies potential wildlife corridors and demonstrates the importance of ensuring that the PAs remain connected in the future.

No previous studies have analysed projections of changes to yields of multiple major crops across the Tana River Basin, so the analysis presented in this thesis provides new insight into how agricultural productivity within the basin is likely to change in the future.

Few studies have examined cross-sectoral impacts at a more local scale in many areas of the world. Indeed, this is the first cross-sectoral GIS analysis of projected climate change impacts and development plans for Kenya.

These gaps must be addressed in order for Kenya to fully understand the impacts of climate change, their potential vulnerability and ways in which they can adapt to the issues. By combining projections of changes across different sectors and the possible interactions between them, this thesis goes some way to achieving this.

2.9 Chapter Summary

This chapter has presented the current state of knowledge and highlighted gaps in the existing literature. Kenya has been confirmed as a country that is projected to be severely affected by climate change, justifying the focus of this study. All of the sectors covered in this research (water resources, biodiversity and agriculture) have been shown to have the potential to be severely affected by climate change.

The following chapters will consider these sectors in turn, before providing a cross-sectoral analysis of the impacts of climate change on the Tana River Basin.

Chapter 3 Overview of Methods

This thesis uses a range of models to explore changes to the Tana River Basin as a result of climate change and land use change. Figure 3-1 shows the drivers of the changes within the basin (climate and land use change) and the sectors which are impacted (hydrology, biodiversity and agriculture). The arrows show the interactions between the drivers and sectors. The interactions between the sectors are split into synergies and trade-offs, based on the possible adaptation measures identified later in this chapter. The diagram shows which chapter or section of this thesis examined each of the drivers and sectors, or the links between them.

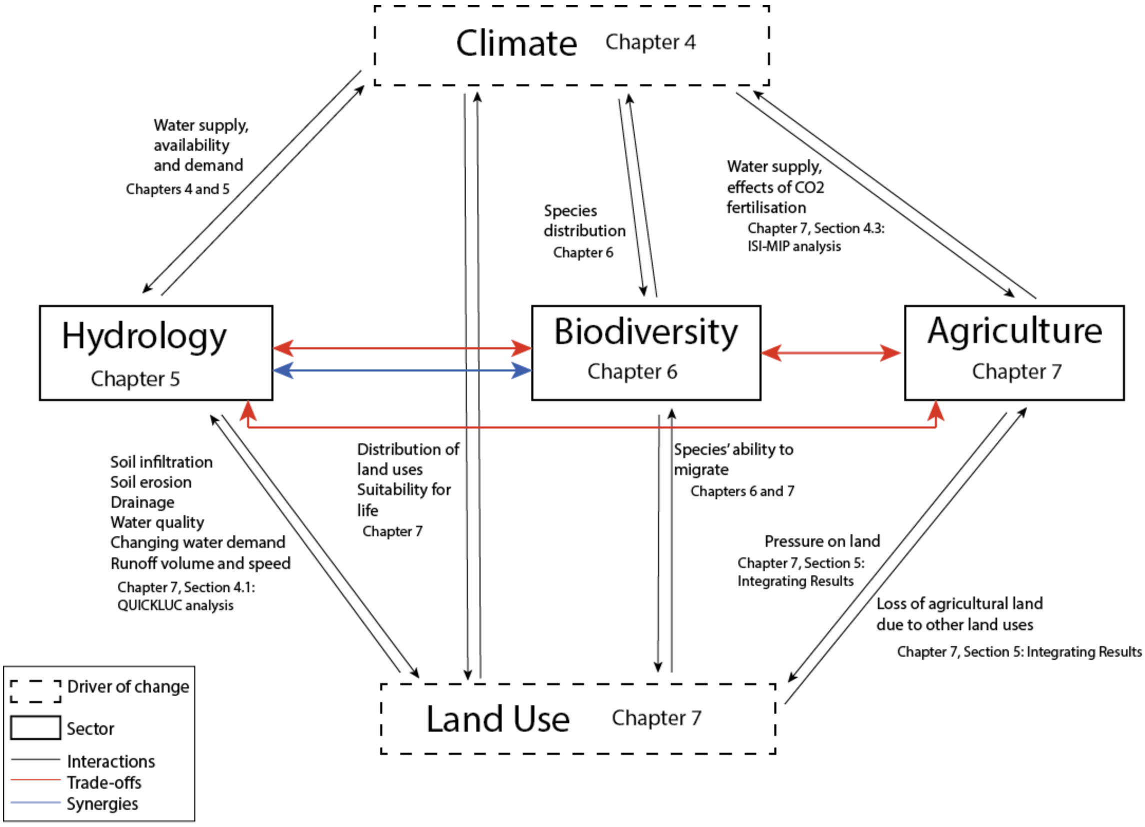

Figure 3-1: Links between the different sections of this thesis

In order to address the aims and objectives stated in Chapter 1, various methods have been employed. An overview of the data sources and methods is shown in Figure 3-2. These data sources and methods were chosen for various reasons. This chapter provides an overview of the types of models available for each sector, as well as explanations for the types of impact model chosen to investigate each sector. The details of the specific models or databases are provided in the corresponding chapter, which are shown on Figure 3-2.

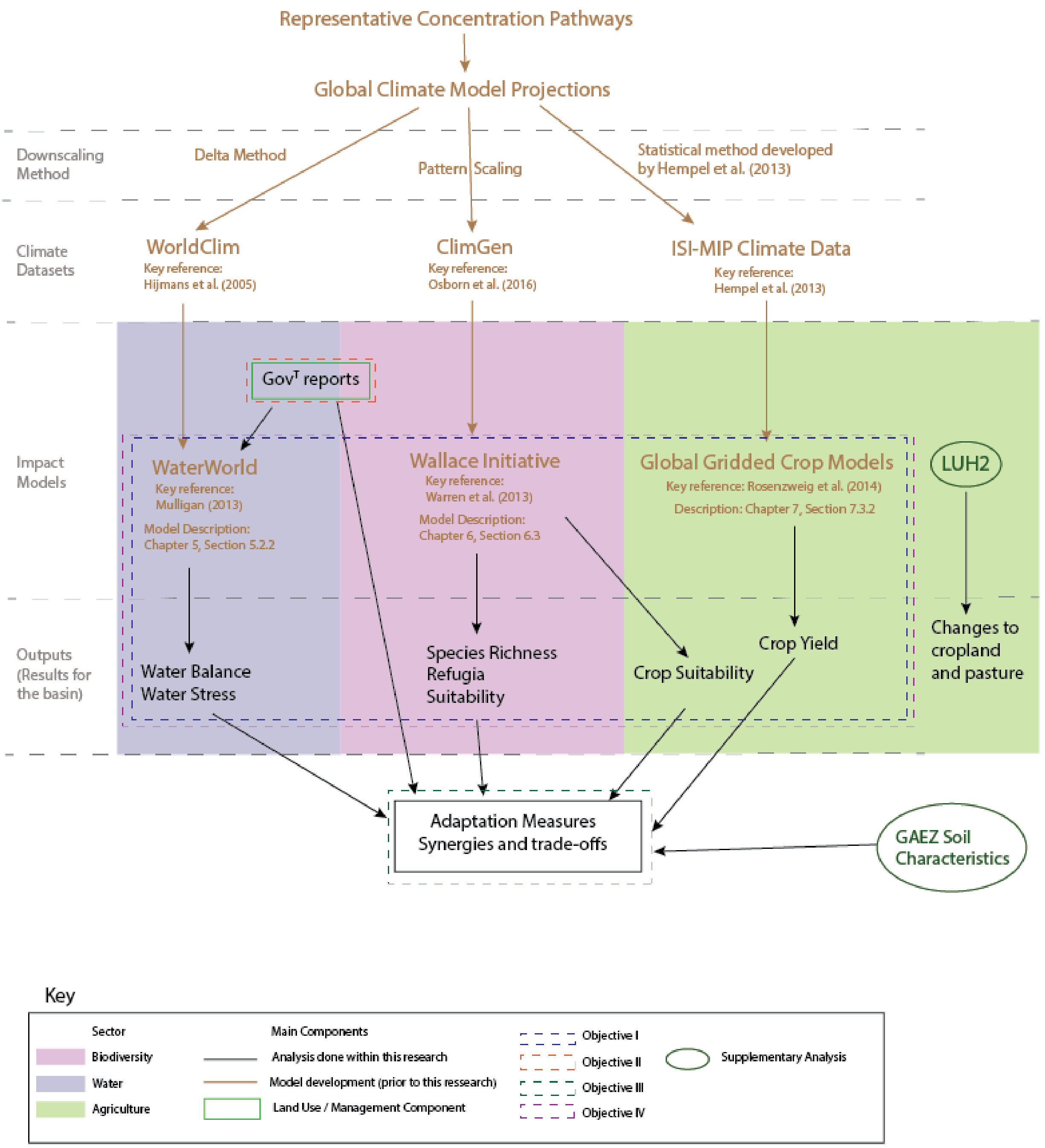

Figure 3-2: Overview of data sources and methods used in this research. Grey text explains the main steps of the methods. Brown text refers to processes and methods that were not done as part of this research (i.e. the methods and models already existed and this research made use of them). Key references for these data sources and models are included in the diagram. Black text refers to the methods and analysis done within this research. Coloured shading shows the different sector (water, biodiversity or agriculture) that the methods are addressing. Green boxes show the origin of the land use or management components. Dashed outlines show the sections where each of the objectives are addressed. Green ovals show supplementary analysis

This chapter will now discuss the different levels of Figure 3-2 (downscaling, climate projections, impact models and adaptation methods) in turn before discussing common sources of uncertainty and limitations with the methods.

3.1 Climate Modelling

Projections of future climates are generated by GCMs. Models from the CMIP5 (Coupled Model Intercomparison Project) have been used for this research. CMIP5 uses the newest generation of GCMs and includes policy intervention and mitigation measures (through the RCPs) (Taylor *et al.*, 2012). Numerous GCMs have been developed by modelling communities around the world and they all project different climate futures. This is because there are differences in the resolutions, numerical methods and parameters in the different GCMs (Stainforth *et al.*, 2007a). Some of the main differences between the individual GCMs are spatial and temporal resolution, errors in the data used to force the models and their parameterisation of unresolved processes (Tebaldi and Knutti, 2007). Simplifications and assumptions are made when producing a GCM, which can lead to errors in its projections. However, GCMs are currently the best way of investigating changes in the climate and associated systems. As all GCMs have a coarse resolution, it is necessary to downscale the models to a finer and common resolution for regional-scale work and impact studies, including use with hydrological models. This is because, at a coarse resolution, the models cannot take into account sub-grid scale features, such as clouds, land cover and topography. These features are important to consider when projecting hydrological change and therefore downscaling of GCM results is necessary (Ramirez-Villegas and Jarvis, 2010). Downscaling refines the coarse output from the GCM, improving realism and making the output more useful to decision-makers. Many downscaling techniques have been developed and they vary in computational and time demands, resolution of the outputs and accuracy (Wilby and Wigley, 1997; Ramirez-Villegas and Jarvis, 2010). Downscaling to a common resolution also provides a way of comparing GCM outputs.

3.2 Downscaling

Various downscaling methods have been developed and these can be broadly split into two categories: statistical downscaling methods and dynamical downscaling methods. No single downscaling method has been found to be superior (Haylock *et al.*, 2006). Statistical downscaling methods use a range of statistical techniques to determine the relationship between the climate patterns produced by the GCMs and locally observed climates. Statistical downscaling methods tend to be easy to apply and produce higher resolution climate surfaces rapidly compared to dynamical downscaling using regional climate models

(Ramirez-Villegas and Jarvis, 2010). By contrast, dynamical downscaling involves using the output from GCMs to drive regional climate models (RCMs) which have a higher spatial resolution and can simulate better the local conditions. However, these dynamical downscaling methods inherit the imperfections of the original GCM and considering finer-scale processes through the RCM can increase the uncertainty of the output.

3.3 Time Horizon of Projections

The 2050s was the main focus of this research. Existing water resources management plans (such as the National Water Master Plan 2030), present strategies for the sustainable management of surface and groundwater resources until the 2050s period. Therefore, focusing on this period will make the modelling conducted in this study relevant to decisions being made now. If modelling work does not focus on timescales relevant to decision-makers, it can be extremely difficult for them to incorporate the science into policy changes. However, longer-term projections are also important so, where possible, the 2070s or 2080s have also been considered.

3.4 The Representative Concentration Pathways

For its Fifth Assessment Report, the IPCC (2014) utilised new emission and concentration scenarios, known as representative concentration pathways (RCPs). These four RCPs present different radiative forcing pathways to 2100 (shown in Figure 3-1). RCP8.5 is a high emissions scenario, RCPs 6.0 and 4.5 are intermediate scenarios and RCP2.6 is a low scenario. RCP2.6 is a ‘peak and decay’ scenario, where radiative forcing reaches a peak in the mid-21st Century and then decreases (Taylor *et al.*, 2012). The 4 RCPs were chosen to represent a broad range of climate outcomes (van Vuuren *et al.*, 2011). Unlike some previous emissions scenarios, the RCPs allow users to analyse futures where policy actions to reduce emissions are taken. The land use scenarios for the RCPs also represent a range of outcomes: from deforestation to net reforestation. While the RCPs represent a wide range of total radiative forcing values, they do not encompass the full range of emissions presented in the literature, particularly for aerosols (Akurut *et al.,* 2014). Utilising all four RCPs in this research will allow for an examination of a full range of climate change futures. Therefore, this research will build on previous work in the Tana Basin (such as Nakaegawa and Wachana (2012), which only used one scenario) by encompassing uncertainties in future global emissions and in regional climate projection.

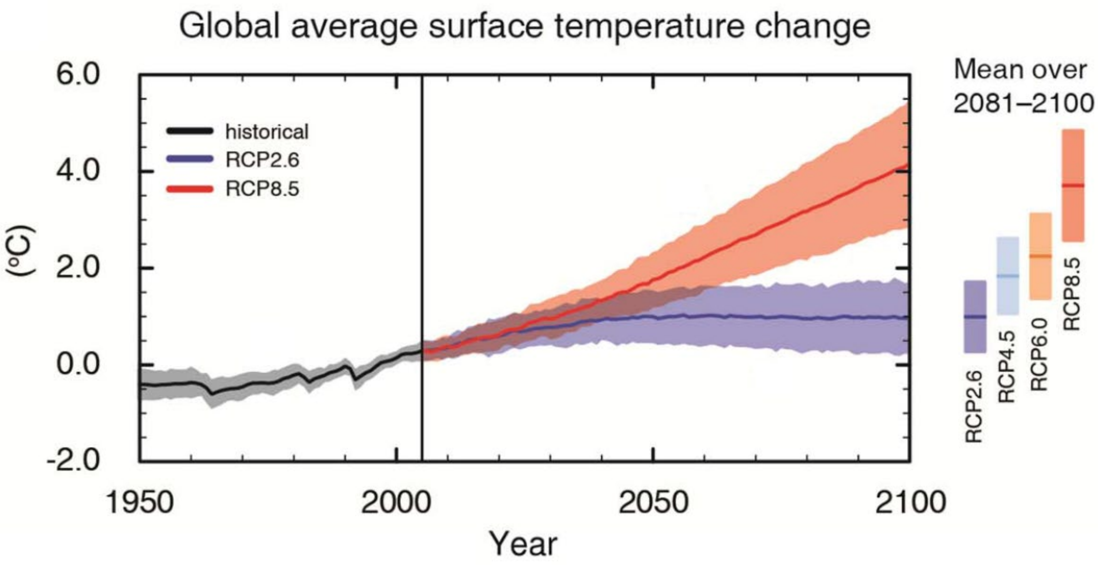

Figure 3-3: The change in global surface temperatures projected for the different RCPs regarding the 21st century (from IPCC, 2014). Coloured shading represents the uncertainty.

Scenarios for land use were included in the development of the RCPs and they were designed to cover a large range of land use projections, as shown in Figure 3-2 (van Vuuren *et al.*, 2011). For RCPs 6.0 and 8.5, the observed growth rate of cropland continues into the future, whereas under RCP2.6 the rate of increase is greater. RCP4.5 sees a decrease in cropland area in the future. Anthropogenically-used grassland also decreases under RCP4.5 and RCP6.0, but increases under RCP8.5. In the RCP8.5 scenario, these increases are generally driven by increases in global population, whereas in RCP2.6 increases in cropland are more linked to bio-energy production. The area of other vegetation continues to decrease under RCP2.6 and RCP8.5, but increases for RCP4.5 and 6.0. As well as global differences in the area of each land use type, the RCPs produce different spatial patterns of change (van Vuuren *et al.*, 2011).

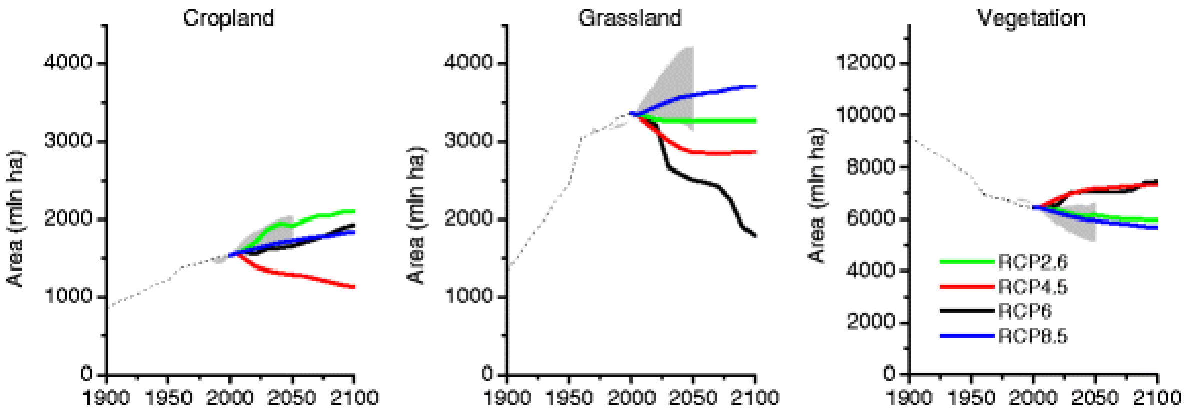

Figure 3-4: Land use (crop land and use of grass land) across the RCPs. Grey area indicates the 90th percentile of scenarios reported in the literature (taken from Smith et al. 2010). Vegetation is defined as the part not covered by cropland or anthropogenically used grassland (van Vuuren et al., 2011)

3.4.1 How do the RCPs relate to the Paris Agreement targets?

The RCPs were developed before the Paris Agreement was proposed, so they are not directly comparable. However, RCP2.6 is the most analogous to a Paris-compliant pathway. Collins *et al.* (2013) showed that, using the CMIP5 models for RCP2.6, there is a 56% probability of exceeding 1.5°C of global temperature rise above 1850-1900 levels and a 22% probability of exceeding 2°C warming by 2080-2100. RCP4.5 is more likely than not to exceed 2°C warming by this time horizon. The other RCPs are likely to exceed both 1.5°C and 2°C by the end of the century.

As recent levels of CO_2 emissions have been closer to the higher end of the RCPs (Friedlingstein *et al.*, 2014), it is still important to consider the implications of these higher climate change scenarios.

3.5 Impact Models

3.5.1 Hydrological Models

Hydrological models have been commonly used for obtaining projections of climate change and its impacts, such as changing river flows (Wilby and Harris, 2006). Hydrological modelling is employed in this research to examine the effects of climate change on the hydrological properties of the Tana River Basin. A large range of hydrological models exist, which vary in complexity and are appropriate for different types of basins and studies. Each has various strengths and weaknesses, so it is important to choose the right model for each application. Refsgaard (1997) argued that there may be no final conclusion on which type of model is better.

This section reviews the different types of hydrological models. Classification of hydrological models is given according to two criteria; process (Section 2.1.1) and spatial (Section 2.1.2) representation.

3.5.1.1 Process Representation

Broadly, hydrological models can be classified, based on the differences in the way they mathematically represent the processes, into empirical, conceptual and physically-based models. Empirical models describe observed behaviour between variables within a system based on observations alone and without considering processes occurring in the system (Abbott and Refsgaard, 1996). Empirical models usually have a high predictive power (Wainwright and Mulligan, 2004) as they are simple and make few assumptions about relationships between variables.

However, their outputs tend to be limited to the location where observed data was collected (Wainwright and Mulligan, 2004). This can also mean that they are time-period specific. For example, land use change in the catchment may result in the derived relationship no longer being applicable.

By contrast, physically-based models are complex models and describe the physical characteristics. Physically-based models attempt to represent all processes as comprehensively and accurately as possible (Krueger *et al.*, 2007). These models are derived from established physical principles and are supposed to produce results that are consistent with field observations (Beven and Feyen, 2002). However, Wainwright and Mulligan (2004) argued that it is often difficult for models to achieve both of these goals and most end up doing one but not the other. Physically-based models have been used in a variety of studies of hydrological processes, climate change and land use change. Physically-based models are often limited by a poor understanding of the processes operating within the system (Beven, 1989) and often do not agree well with observations. As a result, physically-based models are often calibrated against field observations. Many physically-based models require expert knowledge to run (Beven, 1989). More complex models often take more time and resources to run. An example of a physically-based model is MIKE SHE (Refsgaard and Storm, 1995).

Conceptual models lie in between and provide a valuable compromise between empirical models and physically-based models (Seibert and Vis, 2012). Conceptual models represent processes and flows within a system schematically. Examples of conceptual models would be the HBV model (Bergström, 1992) and TOPMODEL (Beven and Kirkby, 1979). They use preconceived ideas of how the system works but the equations describing some flows do not have any true physical meaning as the parameter values cannot be acquired from field measurement. Conceptual models could be considered to have relatively modest data requirements compared to physically-based models (Wheater, 2002) and have a greater explanatory depth than empirical models (Wainwright and Mulligan, 2004).

In summary, physically-based models are often considered as superior to other, simpler ones. However, conceptual models are frequently found to be the reasonable compromise when data demand is considered (Refsgaard, 1997).

3.5.1.2 Spatial Representation

Hydrological models can also be classified based on the spatial representation of the model's inputs and/or outputs. Lumped models aggregate the input and output data across the catchment, so the whole catchment is considered as one computing unit. Many of the earliest hydrological models are classified as lumped models. Lumped models generally require less data and are less prone to equifinality – which is the principle where the same results can be obtained from different model set-ups - (Montanari and Toth, 2007), but are limited by the very fact that they simulate potentially spatially heterogeneous environments as single values (Wainwright and Mulligan, 2004).

By contrast, fully-distributed models try to take the heterogeneity of the landscape into account (Wainwright and Mulligan, 2004). Distributed models have the ability to take account of spatial variation of all parameters and variables within the catchment. Typically, distributed models break the catchment up into discrete units, such as square cells. The majority of physically-based models are distributed models. In between lumped and fully-distributed models, lie the semi-lumped and semi-distributed models. Semi-lumped models aggregate the inputs and outputs by sub-catchments, whereas semi-distributed models often split the catchment into areas of similar land-use, soil or hydrological type.

3.5.2 Species Distribution Models

To investigate changes to biodiversity, this research examined species distribution and how different taxa and individual species may cope under future climatic conditions. Species distribution models (SDMs,also known as ecological niche modelling) aim to provide predictions of species' distributions based on presence or absence data compared to environmental variables (Elith *et al.*, 2006). The relationship between a species' distribution and the environmental conditions it encounters form the basis of these models. Many techniques for modelling species distributions have been developed and these have been widely applied within the fields of biogeography and macroecology (Radosavljevic and Anderson, 2014).

There are two main types of SDM: statistical models and mechanistic models. The former uses statistics to infer the environmental requirements of a species based on their current distribution. The models can then find analogous environments where the species may also occur (Pearson and Dawson, 2003). Statistical

SDMs use more commonly available data and are applicable to a wider range of species. However, the model assumptions cannot stand for novel environments.

By contrast, mechanistic models are process-based models that predict a species distribution from their functional and physiological traits. Mechanistic models directly apply physiological understanding to the prediction of species ranges and provide a greater understanding of the underlying processes (Kearney and Porter, 2009). They can be applied even when data is limited or novel circumstances are being examined (Kearney and Porter, 2009; Evans *et al.*, 2015). Mechanistic models require detailed physiological data, which is seldom available. This makes statistical models more appropriate for studies exploring multiple or even poorly-researched species. The large data requirements of mechanistic SDMs are often cited as a reason for favouring statistical models in climate change conservation studies involving multiple species (Evans *et al.*, 2015). Furthermore, there is often uncertainty over which traits to include in mechanistic SDMs.

This research employs the Wallace Initiative (Price *et al.*, 2013), which links outputs from ClimGen (Osborn *et al.* (2016), described in Chapter 4, Section 4.2) and the MaxEnt (maximum entropy) model (described in Chapter 6, Section), which is a statistical SDM.

3.5.3 Crop Modelling

As agriculture is extremely important in Kenya, an analysis of future changes in yields of major crops has also been conducted. Agricultural models can be broadly split into two categories: process-based and empirical. Empirical models apply existing relationships between crops and climate to predict future outcomes without simulating the processes involved. SDMs, based on the presence of agricultural species, can also be applied to crop modelling. While this method could be considered an oversimplification, it also has advantages, such as simplicity and generality (Beck, 2013).

By contrast, process-based models take information about soils, climate and management practices and feed this information through mathematical models of seed formation and plant growth to simulate the yields using historical and projected future climatic conditions (Roberts *et al.*, 2017). Process-based models include the most detail and many of the parameters in the model have been established through laboratory experiments. However, process-based models must be calibrated to specific locations and may not be scaled-up appropriately for global assessments. Additionally, process-based models cannot account for practices that depend on the behaviour of the farmer, such as fertiliser application (Roberts *et al.*, 2017). Statistical models often use observational data, which means that farmer behaviour can be included implicitly. A challenge with statistical models is that they often fail to portray the non-linearity in crop-climate responses (Challinor *et al.*, 2009b).

This research used outputs of the ISI-MIP project (described in Chapter 7, Section 7.3.2), which compared multiple GGCMs. Using these outputs allowed this research to encompass as many impact models as possible, in order to account for uncertainty arising from the choice of GGCM. The ISI-MIP project provides a readily accessible way of achieving this and indeed this is what ISI-MIP was designed for.

3.5.4 Choosing Models

In all cases, it is important to choose the best model to address the aims and objectives of the research. Here, a mixture of process-based and statistical models were used to answer the objectives set out in Chapter 1.

A process-based, distributed model was chosen to examine changes to hydrology because sparsely gauged river basins, like the Tana, allow little opportunity for the development of empirical models, which require observations. Furthermore, the multi-faceted nature of the problem being examined in this research, means that an understanding of the processes is necessary to analyse the impacts of scenarios of changes (Mulligan, 2013b). As this research also involved examining the impact of land cover changes on hydrology, sufficient spatial detail is needed for land use or management, supporting the use of a fully-distributed model. This need for changing land cover also demonstrates the importance of running a hydrological model specifically for this research, rather than using the outputs of hydrological inter-comparison projects.

To examine changes to biodiversity, database that employed a statistical SDM was chosen. As stated in Section 3.5.2, statistical techniques are better for examining a wide range of species because the data required to run mechanistic models is not widely available. As Objective I aimed to examine changes in biodiversity, rather than single species, this method was most appropriate.

On the other hand, as specific crops were analysed for the agricultural analysis, process-based models were more appropriate. However, as limited data is publicly available for the basin, the results of an existing modelling exercise which used process-based crop models (ISI-MIP) was used here. Results of likely changes in yield from process-based crop models were complimented by statistical SDM results for the changes in suitability of some species. This allowed for an analysis of a wider range of crops types and forestry species that are important in Kenya. The results of the statistical SDM for crop types could be seen as less useful as it only considers changes in suitability. Although areas may remain suitable for certain crops in the future, the potential change in yield (either higher or lower) are not possible to see. Additionally, the SDMs used here cannot differentiate between specific varieties and only consider crop types.

3.6 Addressing Adaptation

Various approaches have been used to assess adaptation and applying modelling techniques is only one approach. Modelling the impacts of climate change and assessing adaptation using the results is referred to by the IPCC as a 'top-down' adaptation approach (Noble *et al.*, 2014). An alternative is place-based research, which uses detailed site-specific and/or context-specific information to assess adaptation options (Beveridge *et al.*, 2018). This is similar to 'bottom-up' adaptation (Noble *et al.*, 2014) described in the IPCC reports, which focuses on what makes systems or communities vulnerable. Place-based research into climate change adaptation is often linked to value-based perspectives (O'Brien and Wolf, 2010) because of their focus on integrating scientific knowledge with local experiences. These methods are bound to a specific geographical area and culture, which can be useful for policymakers as the methods link more closely to local risks and values (Adger *et al.*, 2011; Raymond and Brown, 2011). Beveridge *et al.* (2018) reviewed the crop modelling literature based on Central America and found that modelling approaches do not consider a range of on-farm adaptation strategies (such as conservation agriculture, fruit tree planting and building windbreaks), which were represented in place-based studies. Modelling studies tended to focus only on changing the planting date, cultivar or area cultivated, as well as using irrigation or fertilisers (Beveridge *et al.*, 2018).

However, Nobel *et al.* (2014) also noted that, in practice, these two approaches are often combined, as assessments of adaptation options have become very complex. Therefore, both approaches can still be seen as useful. Place-based research would not have been appropriate for this research due to the lack of detailed, publicly available, local information available for the Tana River Basin. These in-depth, place-based research projects also often cannot consider the longer timescales necessary for climate change adaptation (O'Neil and Graham, 2016; Beveridge *et al.*, 2018). In addition, as the Tana River Basin covers a large area, with many different ecosystems, climate risks and community groups, place-based research would have required greater time and resources.

3.7 Common Sources of Uncertainty and Limitations

3.7.1 Uncertainties Arising from Input Data

GCM uncertainty must be acknowledged in order to fully understand the results and ultimately facilitate decision-making. Uncertainty can arise from parameter values or model structures. Using all the CMIP5 models available will demonstrate the uncertainty in the model projections by showing the full range of projections. Uncertainty can be more fully explored by combining different models and scenarios and performing ensemble modelling (Déqué *et al.*, 2007). Using numerous models to inform climate change predictions creates the most realistic results, taking into account several sources of uncertainty. Uncertainties in rainfall changes are greater than those associated with temperature change. As precipitation is a main input for hydrological models, the uncertainties are vital to consider. Using the full range of CMIP5 models and the ensemble mean goes some way to addressing this uncertainty.

For species distribution modelling, it is also important to consider the biodiversity input data. Species' distributions are not exactly known (Elith *et al.*, 2006), creating uncertainty in the results of the Wallace Initiative and other species' distribution modelling work. Poor or uneven sampling across environmental space can lead to erroneous model results. In some cases, there is not sufficient data available to fully inform the model as to the true distribution of a species (Stockwell and Peterson, 2002; Wisz *et al.*, 2008). Fourcade *et al.* (2014) argue that datasets used to drive the SDM are often biased because of an unequal sampling effort across the study area. This spatial sample bias is not always present (Loiselle *et al.*, 2008). Despite efforts to clean the data, it is possible that there are geographical or taxonomic inaccuracies in the species occurrence records. Uncertainty can also arise from limitations with the environmental input data (Kriticos and Leriche, 2010).

3.7.2 Structural Uncertainty

Structural uncertainty arises from the differences in model set up and resolutions (Curry and Webster, 2011). Many model comparison projects, such as CMIP5, have common boundary conditions and output formats agreed between the GCMs involved. However, differences in the construction or structure of models (such as numerical techniques and the extent of use of physical parameters) cannot be controlled.

3.7.3 Incomplete Knowledge of the System

Berkes (2007) argued that natural and human systems are so complex that our understanding of them will never be complete. Although the importance of acknowledging uncertainties is generally well known, their irreducible nature is not generally appreciated. Stainforth *et al.* (2007b) demonstrated that even the most complex climate models available today do not realistically represent the real-world climate system. Although many model developments have been made since this statement was made, model development is a complex and iterative process. Our understanding is gradually increasing but challenges remain (Flato *et al.*, 2013). Some processes, particularly those responsible for inter-annual and multi-decadal variability, are still not well presented in the latest generation of climate models. GCMs cannot anticipate some tipping points in the Earth system and GCMs have poor representations of processes that are important to shorter term climate variability, such as ENSO. Wang *et al.* (2014) show that there is a large scale bias in CMIP5 coupled models, which they believe is linked to the AMOC being too weak. All model estimations must be evaluated as potential scenarios only.

There are a number of limitations with climate models that are specific to East Africa. Yang *et al.* (2015) show that models do not accurately represent the relationship between the long rains and sea surface temperatures on long time scales. SST biases in the models cause them to overestimate the short rains and underestimate the long rains. They also use historical runs to show that the CMIP5 multi-model mean overestimates East African rainfall in the majority of months. Yang *et al.* (2015) show that although coupled models tend to misrepresent the pattern of East African rainfall, the implications of this for projections from these models remains uncertain. In addition, East Africa is subjected to orographic rainfall patterns, which is where the precipitation is influenced by the local topography (Oettli and Camberlin, 2005; Hession and Moore, 2011). Rainfall tends to be concentrated upwind of the mountain range, which is poorly resolved in GCMs.

Furthermore, the Indian Ocean Dipole (IOD) is an important cause of climate variability in this region, as discussed in Chapter 2, Section 4. However, high uncertainty remains as to how the IOD may be affected by climate change and it is not represented well in the current climate models (Conway *et al.*, 2007). Similarly, potentially rapid changes in the ENSO are not well represented in GCMs. Rapid changes in ENSO could have serious, large scale impacts on atmospheric circulation and rainfall across the tropical Pacific. Mason and Goddard (2001) show that failure of the short rains over East Africa has a strong relationship with La Nina conditions. However, modelling can be seen to be invaluable when uncertainties are acknowledged and the model is applied correctly.

3.7.4 Inability to Consider (ECEs) Inter-annual Variability

The importance of ECEs to all three sectors (water, biodiversity and agriculture) was shown in the Literature Review (particularly in Section 2.3.5). The methods chosen for this research mean that extreme events could not be considered, which is a major limitation. Similarly, this research only considered changes to the mean climate and was not able to assess inter-annual variability. To date, much research has focused on changes to the mean climate, while the effect of extremes have received relatively less attention. Assessing the change to the mean climate was the focus of this study. The models chosen for the water and biodiversity sections of this analysis cannot simulate climate variability or extremes. To make the agricultural analysis comparable, only the average was analysed. Examining the impacts of extreme events and climate variability was outside the scope of this study.

Figure 3-5 shows the effect of changes in temperature distribution on extremes (IPCC, 2012). A shift of global climate to the right (shown in Figure 3-5a) leads to more frequent hot weather events. Figure 3-5b shows an increase in variability of climatic variables, which leads to a higher number of both extreme hot and cold events. However, as these changes do not occur separately, it is important to consider the synchronous effects, which is shown in Figure 3-5c. This shows that more hot weather events are likely along with a similar number of cold weather events as presently occur. As well as increased variability influencing temperature extremes, it will also alter precipitation (IPCC, 2012).

However, there are challenges with researching the impact of extreme events. The IPCC (2012) stated that, despite available data for temperature and precipitation, other important variables (such as soil moisture or extreme wind speeds) are poorly monitored at sufficient temporal and spatial resolutions. In addition, it is difficult to quantify the impact of extreme events due to data scarcity of past events (IPCC, 2012) and inconsistent definitions of what is classed as an extreme event (Bailey and van de Pol, 2016). Understanding how extreme events have changed in the past is important to understanding future effects.

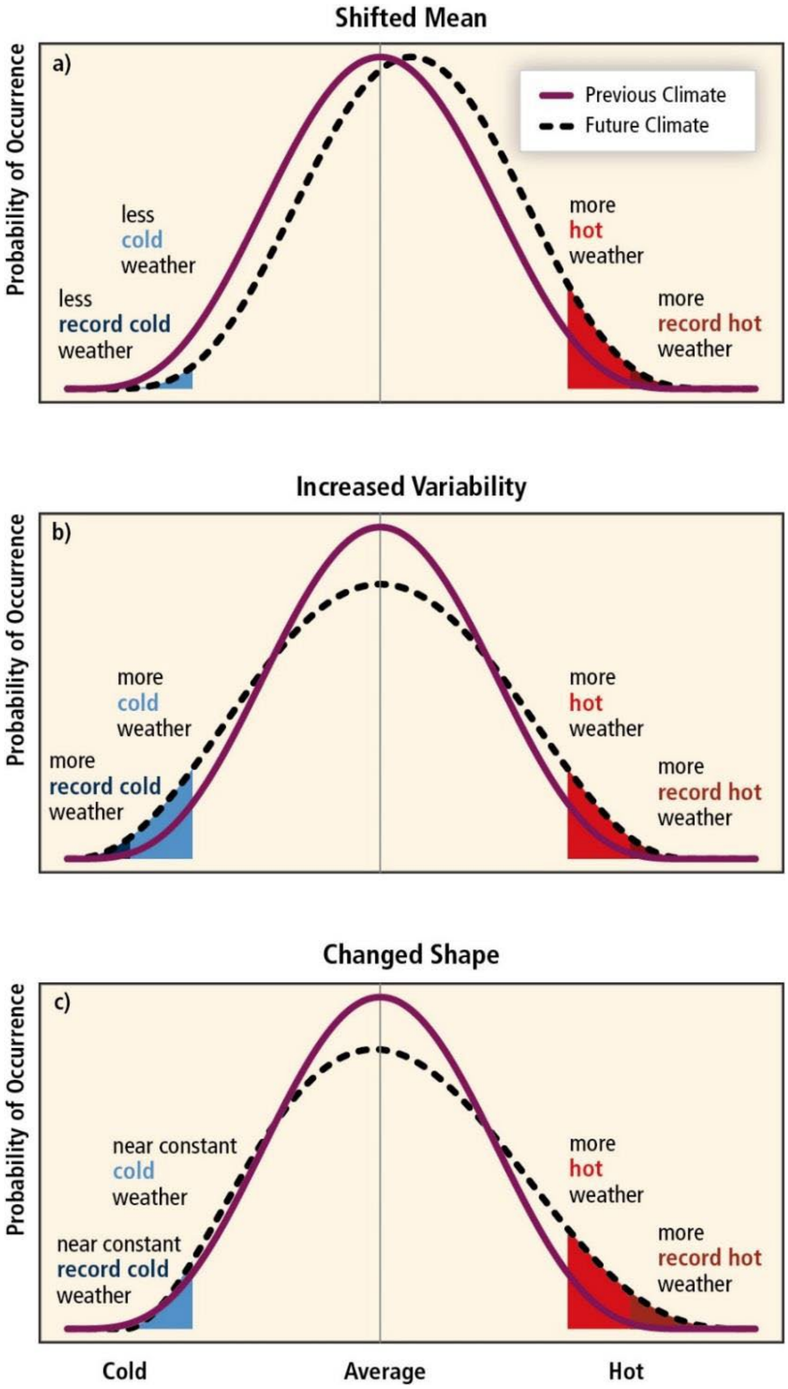

Figure 3-5: effect of changes in temperature distribution on extremes. Different changes in temperature distributions between present and future climate and their effects on extreme values of the distributions: a) effects of a simple shift of the entire distribution toward a warmer climate; b) effects of an increased temperature variability with no shift of the mean; and c) effects of an altered shape of the distribution, in this example an increased asymmetry toward the hotter part of the distribution. (IPCC 2012)

3.8 Overall Confidence in Methods

Each method chosen for this research includes various assumptions and limitations, so it is important to consider confidence in the results. Levels of confidence in results of modelling studies depend on several factors, such as the choice of model, the number of climate models used as inputs or the number of impact models used for a comparison study.

The biggest source of uncertainty for crop modelling studies has been shown to be GGCM choice (Muller *et al.*, 2017; Ostberg *et al.*, 2018), so examining a range of crop models was important to improving confidence in the results. A smaller range of GCMs and RCPs were considered for agriculture than for water and biodiversity, but employing the results of multiple crop models improves the confidence in these results. Model runs from the ISI-MIP project were used in this research because they provided readily available projections using many of the leading crop models from modelling groups around the world.

For the hydrological modelling, the WaterWorld model was chosen largely as a compromise based on limited data availability and its ability to model sparsely gauged basins (see Chapter 5, Section 5.2 for details). One caveat to note is that the dams on the Tana River could not be modelled in WaterWorld, so it is possible that this part of the work is less realistic. However, as the impact of dams or changes in streamflow were not the focus of this research, this is not a major limitation. Using the WaterWorld model allowed for a comparison between large numbers of GCMs and between all four RCPs, to assess the uncertainty (as per Objective IV). An alternative method would have been to use the ISI-MIP hydrological projections to provide a comparison between different global hydrological models. However, these models are known to significantly overestimate runoff (Davie *et al.*, 2013).

In terms of biodiversity, there are a number of caveats which could mean that the results are an over- or under-estimate. These limitations are fully discussed in Chapter 6, Section 6.6.7. Confidence in the results comes from the large number of GCMs (21) and RCPs (4) considered, as well as the two dispersal scenarios (no dispersal and realistic dispersal) employed.

Chapter 4 Current Climate and Future Projections

4.1 Introduction

The aim of this chapter is to explore the current climate and projected changes for the Tana Basin. Before the impacts of climate change on the key sectors can be addressed (Objective I), it is important to determine how the climate is projected to change. This chapter will focus on the main climate variables: temperature and precipitation. First, the climate datasets are described in Section 2, then the current climate of the Tana River Basin are presented (Section 3). Section 4 presents the results of the model validation, which compares the climate data to observations. Section 5 then presents projected changes to temperature and precipitation, before these results are discussed in Section 6. By considering a range of models and climate change scenarios, this chapter also addresses Objective IV, which focused on understanding uncertainty.

4.2 WorldClim and ClimGen

This research utilises WorldClim (Hijmans *et al.*, 2005) climate data, but also compares it to another dataset, ClimGen (Osborn *et al.*, 2016). WorldClim downscaled data is provided by the WaterWorld policy support system. WorldClim is a set of global climate grids, with a spatial resolution of 30 arc-second (about 1km^2). These grids were produced using data from weather stations around the world and have a much higher spatial resolution than previous climate surfaces. For projected climate data, WorldClim uses a statistical downscaling method known as the delta method. The delta method produces an interpolated surface of changes in climates (known as deltas or anomalies) and then applies the surface to a baseline climate (for WorldClim, this is 1950-2000). The Delta method only represents changes in the mean climate and does not represent the variability. This method makes several assumptions about changes in climate (Ramirez-Villegas and Jarvis, 2010). Firstly, the Delta method assumes that changes in climate vary only over large distances; namely the distances covered by a GCM's grid cell. Additionally, this downscaling method assumes that relationships between the variables in the baseline (current) conditions are likely to be maintained in the future. These assumptions show the limitations of this method, as they might not hold true; particularly in heterogeneous landscapes where sub-grid influences on climate are significant.

ClimGen (developed from Mitchell *et al.*, 2004 by Osborn *et al.*, 2016) is a pattern scaling model which provides monthly climate variations at a 0.5° x 0.5° resolution for the terrestrial land surface. The model outputs can be annual, seasonal or monthly. ClimGen uses a pattern scaling approach to obtain the regional patterns of climate change for a given change in global mean temperature (Warren *et al.*, 2012; Osborn *et al.*, 2016). Pattern scaling refers to the assumption that the pattern of change simulated by coupled atmosphere-ocean GCMs (AOGCMs) is relatively constant under a range of warming rates (Lopez *et al.*, 2014). The technique takes the spatial pattern of climate change produced by a GCM and scales its magnitude by the global temperature from a simple climate model (Mitchell, 2003). In order to simulate change in precipitation (both precipitation variability and change in the mean precipitation), ClimGen uses a gamma shape method, which represents the temporal distribution of the precipitation. The change in this output is then scaled by the global mean temperature change (Osborn *et al.*, 2016).

One advantage of this is that it negates the need for bias correction, as biases are generally disregarded when examining the climate pattern (Osborn *et al.*, 2016). Osborn *et al.* (2018) recently tested the performance of pattern scaling and found that, for temperature rises of up to 3.5°C, pattern scaling was able to closely emulate GCM simulations. As seen with the delta method used for the WorldClim data, pattern scaling makes a number of assumptions though is generally seen as an accurate method of downscaling (Mitchell, 2003). The first assumption made is that the simple climate model, in this case MAGICC, adequately represents the GCM. In addition, a major underlying assumption is of a linear relationship between global mean temperature change and local climate change. However, Osborn *et al.* (2016) argue that this should be seen as an 'approximation' rather than an assumption in order to assess its accuracy.

WorldClim and ClimGen are effectively bias-correction downscaling methods whereby the bias in the GCM's mean climate is corrected by only using the change fields from the GCM and combining these with an observed climatology for present-day climate. In ClimGen (Osborn *et al.* 2016), the changes in the variability of monthly precipitation as simulated by the GCMs are also used. This is the equivalent to bias-correction of both mean and monthly variability biases for precipitation. The climate projections from both WorldClim and ClimGen have a simple form of statistical downscaling, in the sense that they interpolate the GCM change fields to a fine resolution grid (30 arc-seconds for WorldClim, 0.5° for ClimGen) and combine (via the delta method) these changes with the observed climatology that is already on the fine grid. This interpolation does not incorporate any additional information about local-scale climate that is typically included in more sophisticated statistical downscaling methods (with the exception of the land-ocean boundary which is included in the ClimGen interpolation) but they do have the advantage over more sophisticated methods that they can be applied to the global land surface.

Using downscaled datasets enables a comparison between different GCMs. This is necessary as the different GCMs can project different patterns of warming and changes in other climatic variables, particularly precipitation. The IPCC (2014) has shown that some GCMs project increases in precipitation in areas where other GCMs expect decreases in precipitation in the future. Otieno and Anyah (2013) used six earth system models to project annual and seasonal changes in precipitation across the Greater Horn of Africa and found that some models predict a wetter climate and others project a decrease in rainfall. Figure 4-1 shows the number of models projecting increases in precipitation across Africa from the IPCC (2007). For the annual mean and DJF, the majority of the models project wetter conditions across East Africa and drier conditions in the north of the continent. By contrast, there is no strong agreement in projections for East Africa for JJA. This is also seen for southern Africa in DJF. In all three cases (annual, DJF and JJA), there are areas of Africa where only half of the models project increases in precipitation, demonstrating the uncertainty between the individual GCMs in this region. As well as differences in the sign of the change, GCMs disagree on the magnitude of precipitation change. Hawkins and Sutton (2011) quantified the percentage of uncertainty in precipitation change from different sources and found that model uncertainty is the dominant cause in most regions. By the end of the century, model uncertainty represents 60-90% of the total uncertainty whereas emissions scenario uncertainty and internal variability were minor factors in comparison.

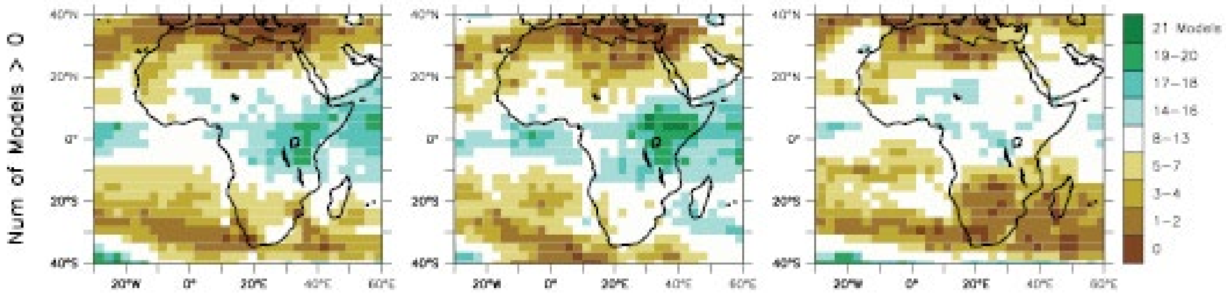

Figure 4-1: Precipitation changes over Africa from the MMD-A1B simulations. Number of models out of 21 that project increases in precipitation. From left to right: Annual mean, DJF and JJA. Taken from IPCC (2007)

Table 4-1 lists the CMIP5 GCMs available from WorldClim via WaterWorld for the four different RCPs. 15 GCMs are available for RCP2.6, 19 GCMs for RCP4.5, 12 GCMs for RCP6.0 and 17 GCMs available for RCP8.5. The projected changes in Section 4.5 make sure of these GCMs.

Table 4-1: CMIP5 GCMs available in WaterWorld (Mulligan, 2013b) downscaled by WorldClim (Hijmans et al., 2005)

GCM		Resolution (degrees)	Modelling Centre	RCP			
				2.6	**4.5**	**6.0**	**8.5**
ACCESS1.0	AC	1.25 x 1.8	Commonwealth Scientific and Industrial Research Organisation		Y		
BCC-CSM1-1	BC	2.8 x 2.8	Beijing Climate Center	Y	Y	Y	Y
CCSM4	CC	1.25 x 0.94	National Centre for Atmospheric Research	Y	Y	Y	Y
CESM1-CAM5-1-FV2	CE	1.25 x 0.94	Centre National de Recherches Meteorologiques		Y		
CNRM-CM5	CN	1.4 x 1.4	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	Y	Y		Y
GFDL-CM3	GF	2.0 x 2.5	Geophysical Fluid Dynamic Laboratory	Y	Y		Y
GFDL-ESM2G	GD	2.5 x 2.0	Geophysical Fluid Dynamic Laboratory	Y	Y	Y	Y
GISS-E2-R	GS	2.0 x 2.5	NASA Goddard Institute for Space Studies	Y	Y	Y	Y
HadGem2-AO	HD	1.88 x 1.25	National Institution of Meteorological Research/Korean Met. Administration	Y	Y	Y	Y
HadGem2-CC	HG	1.88 x 1.25	Met Office Hadley Centre		Y		Y
HadGem2-ES	HE	1.88 x 1.25	Met Office Hadley Centre	Y	Y	Y	Y
INMCM4	IN	2.0 x 1.5	Institute for Numerical Mathematics		Y		Y
IPSL-CM5A-LR	IP	3.75 x 1.8	Institut Pierre-Simon Laplace	Y	Y	Y	Y
MIROC5	MC	1.4 x 1.4	Atmosphere and Ocean Research Institute (The University of Tokyo)	Y	Y	Y	Y
MIROC-ESM	MR	2.8 x 2.8	Japan Agency for Marine-Earth Science & Technology	Y	Y	Y	Y
MIROC-ESM-CHEM	MI	2.8 x 2.8	Japan Agency for Marine-Earth Science & Technology	Y	Y	Y	Y
MPI-ESM-LR	MP	1.8 x 1.8	Max Planck Institute for Meteorology	Y	Y		Y
MRI-CGCM3	MG	1.1 x 1.1	Meteorological Research Institute	Y	Y	Y	Y
NorESM1-M	NO	2.5 x 1.9	Norwegian Climate Centre	Y	Y	Y	Y
TOTAL NUMBER OF GCMS				**15**	**19**	**12**	**17**

4.3 Kenya's Current and Recent Climate

Before considering the climate change projections, it is necessary to examine the current climate of Kenya. Data on the current and recent climate in the Tana River Basin has been obtained from CRU TS 3.22 (Harris *et al.*, 2014) and from WorldClim (Hijmans *et al.*, 2005). Due to its equatorial location, there is little annual variation in temperature. The mean annual air temperature, from the WorldClim data, is 24.6°C. Figure 4-2 shows the basin-average monthly mean temperature and total precipitation. Monthly average temperatures in the Tana Basin range from a maximum of 26.2°C in March to a minimum of 22.6°C in July. Seasonally, highest mean temperatures occur in the MAM season. The bimodal rainfall pattern is clear, with peaks of 142 mm/month and 180 mm/month in April and November respectively.

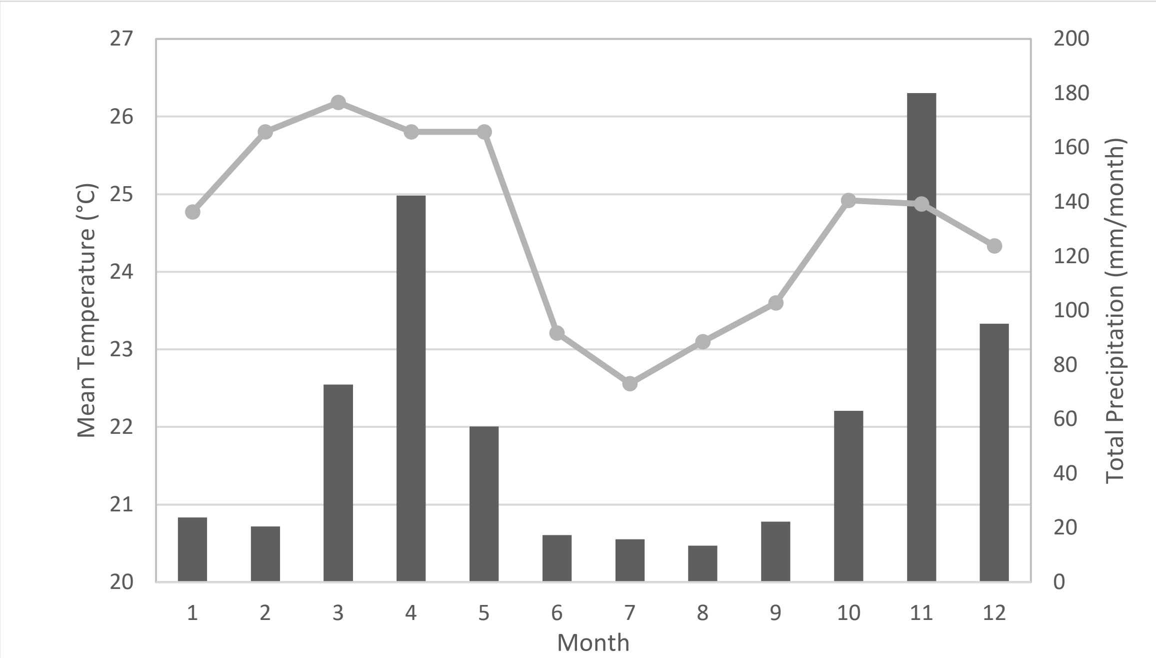

Figure 4-2: Baseline (1950-2000) basin-average monthly mean temperature and total precipitation using the WorldClim baseline climatology (from WaterWorld, 2016)

However, both temperature and precipitation are extremely spatially variable in the Tana Basin, as shown in Figure 4-3.

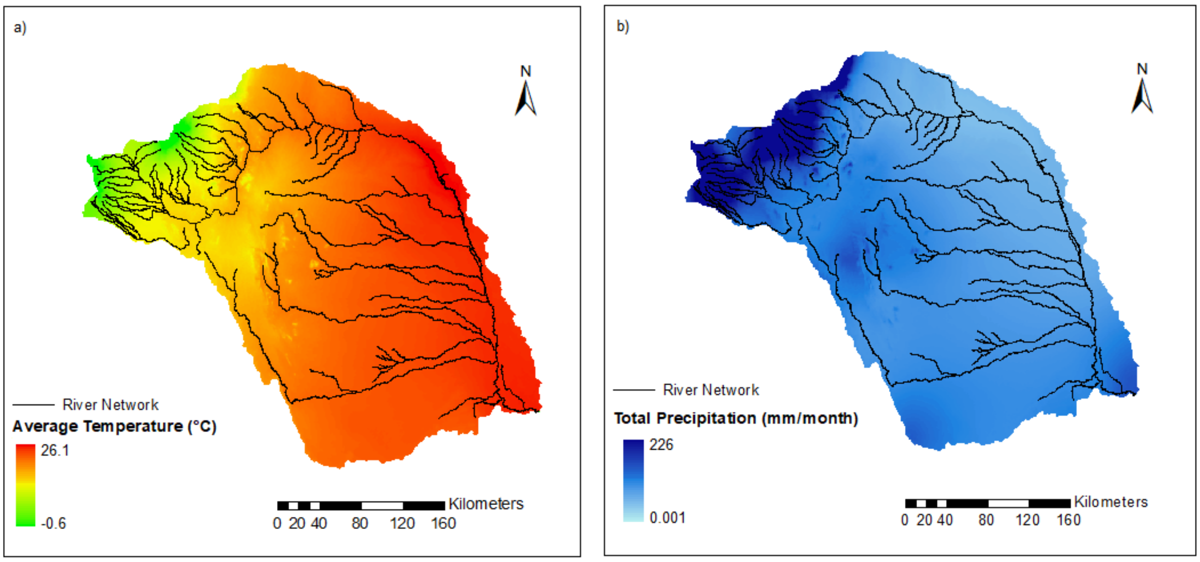

Figure 4-3: Spatial variability of (a) mean annual temperature and (b) total annual wind-corrected rainfall (mm/month) in the basin for baseline conditions, from WorldClim baseline (WaterWorld, 2016).

The majority of the rainfall is concentrated in the higher elevations in the north of the basin. The area with the highest elevation and topographical range are where the lowest average annual temperatures are seen. In addition, Kenya, and specifically the Tana Basin, are characterised by a huge topographical range; from sea level to 5199m ASL at the Batian Peak of Mount Kenya, as shown in Figure 4-4. Precipitation is strongly influenced by this topography, as shown in Figure 4-5, which shows the relationship between elevation and rainfall in the basin. However, the presence of large water bodies, such as Lake Victoria and Lake Turkana, is also important in determining rainfall patterns. Kenya experiences bimodal rainfall peaks, with the short rains occurring November – December and the long rains between March and May. On average, the wettest months are April and November. Kenya experiences both floods and drought conditions at various times throughout the year. Ongwenyi *et al.* (1993) have shown that a number of severe droughts occurred between 1930 and 1990. In addition to this, major floods have been recorded in the low-lying parts of the Lake Victoria catchment and the Tana Basin. One particular year of note, with regards to flooding, was 1961, when heavy rainfall led to widespread floods across much of the country.

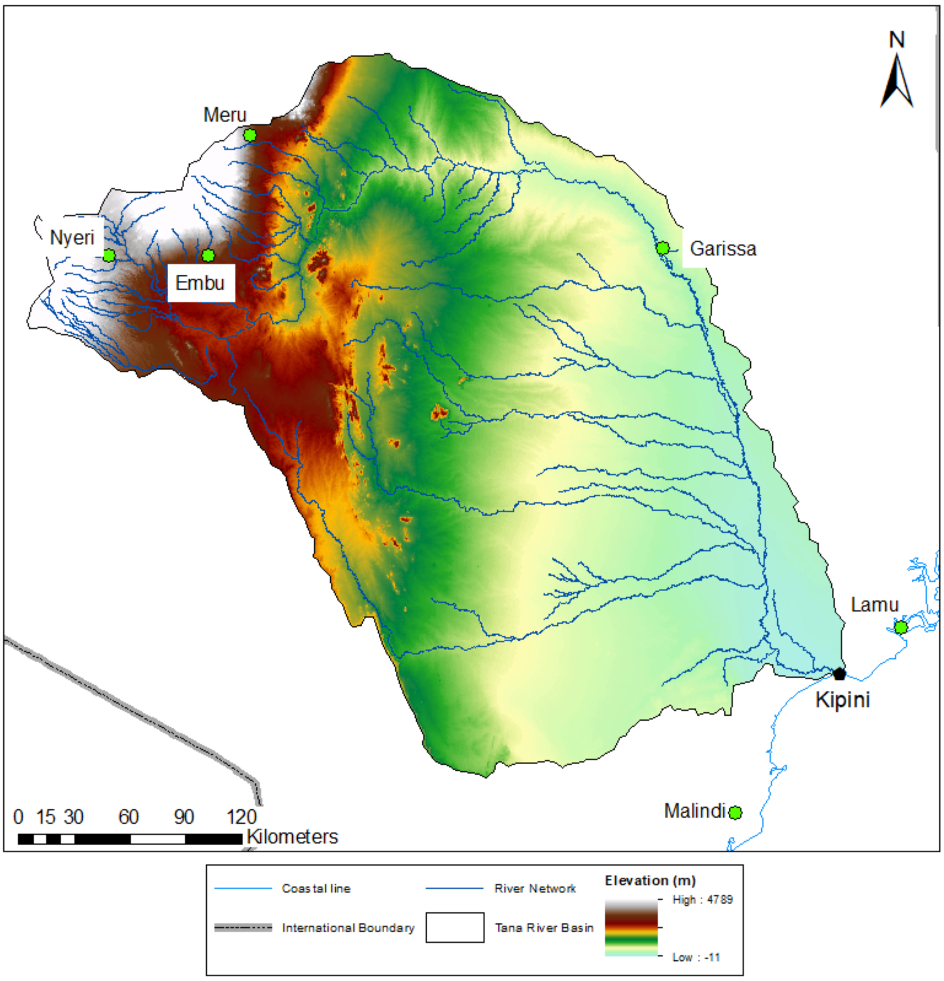

Figure 4-4: Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) of the Tana River Basin. The black circle shows the outlet of the main Tana River. The river network is overlaid in blue. Green circles show towns in and around the basin where rain gauges were present and have been used in this research.

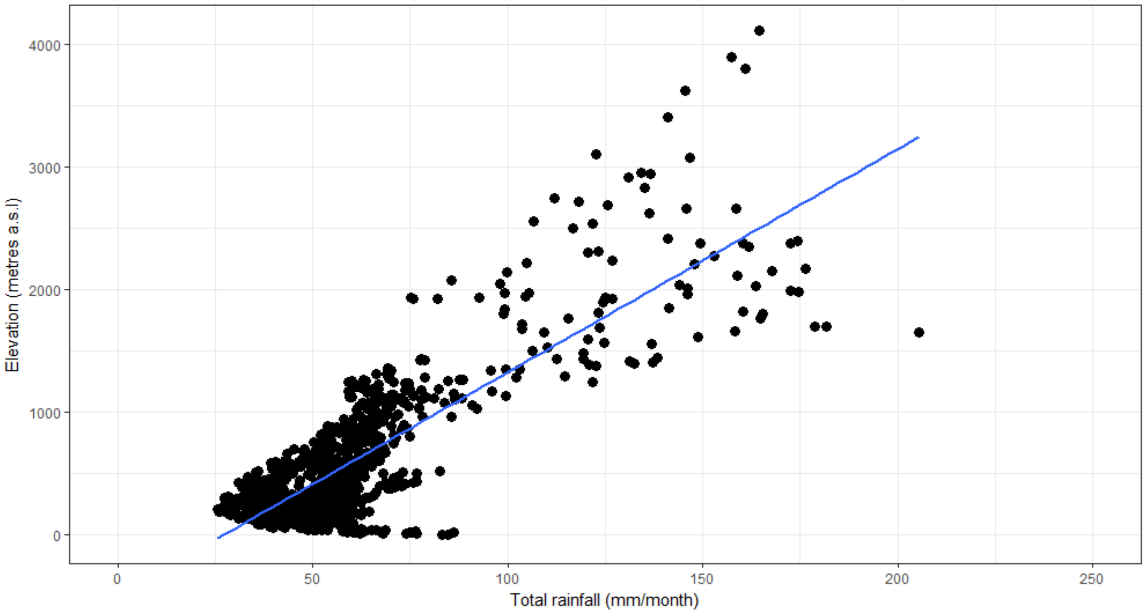

Figure 4-5: Scatterplot showing the relationship between elevation (in metres above sea level) and basin-average total rainfall (mm/month) for the average of 1950-2000 for each 1-km² grid cell within the Tana River Basin (Data from: WaterWorld, 2016).

4.3.1 Recent Climate Changes

The temperature in the basin has already changed in recent decades. Table 4-2 shows the observed monthly temperatures for the Tana River Basin for 1961-1990 and 1984-2013, as well as a comparison between the two periods. This is based on CRU TS 3.22 data (Harris *et al.*, 2014). The warmest season is shown to be MAM. There has been an observed increase in average temperatures of between 0.25 and 0.41°C between 1961-1990 and 1984-2013.

Table 4-2: Observed Average Monthly Temperature (°C) for the Tana River Basin for the periods 1961-1990 and 1984-2013, with the difference between the two time periods. Data for March for the period 1961-1990 was not available, so the cells are left blank.

MONTH	1961-1990			1984-2013			Difference between 1961-1990 and 1984-2013 avg	Diff between max and avg		Diff between min and avg	
	Min	Avg.	Max	Min	Avg.	Max		1961-1990	1984-2013	1961-1990	1984-2013
1	24.2	25.5	27.0	24.2	25.8	27.3	0.4	1.5	1.4	-1.2	-1.6
2	25.6	26.5	27.6	25.7	26.9	27.8	0.4	1.1	0.9	-0.9	-1.2
3				25.9	27.4	28.5			1.1		-1.5
4	25.2	26.4	27.9	25.3	26.7	28.2	0.3	1.5	1.5	-1.2	-1.5
5	24.1	25.1	26.5	24.4	25.5	26.6	0.4	1.3	1.2	-1.1	-1.1
6	22.4	23.8	24.9	23.3	24.1	25.2	0.3	1.1	1.0	-1.4	-0.9
7	21.9	23.1	24.1	22.8	23.4	24.8	0.3	1.0	1.4	-1.2	-0.6
8	22.9	23.8	24.7	23.1	24.1	25.7	0.3	0.8	1.6	-1.0	-1.0
9	23.0	24.2	25.2	23.9	24.6	25.6	0.4	1.0	1.0	-1.2	-0.7
10	24.3	25.6	26.6	24.9	26.0	27.1	0.4	1.1	1.1	-1.2	-1.1
11	24.5	25.5	26.6	24.5	25.8	27.4	0.3	1.1	1.6	-1.1	-1.3
12	23.4	25.1	26.4	24.3	25.4	27.3	0.4	1.3	1.9	-1.7	-1.2

Table 4-3 shows the observed average monthly precipitation for the basin, based on the data from CRU TS3.22 (Harris *et al.*, 2014). It is clear that there are significant differences in average monthly rainfall in the Tana River Basin, as previously seen in the WorldClim data. The overall changes in average monthly precipitation have been minor between 1961-1990 and 1984-2013 in the majority of months. Drying is observed in all months except January, November and December. April shows a more significant drying than other months. The extremes show a stronger change, which show a drying trend. The wettest years are less wet for the majority of months (except May and November). However, the Met Office (2011) show that the limited precipitation data for Kenya makes it difficult to identify trends, but that some evidence of drying is apparent.

Table 4-3: Observed Average Monthly Precipitation (mm/month) for the periods 1961-1990 and 1984-2013, with the difference between the two time periods. The months of peak rainfall are highlighted in grey. Values are presented to the nearest mm.

Month	1961-1990			1984-2013			Difference between 1961-1990 and 1984-2013 avg.	Difference between wettest and average		Difference between driest and average	
	Wettest	Avg.	Driest	Wettest	Avg.	Driest		1961-1990	1984-2013	1961-1990	1984-2013
1	175	36	0	112	41	0	5	139	71	-36	-40
2	121	25	0	90	20	0	-6	96	70	-25	-20
3	217	64	2	189	63	4	-1	153	127	-62	-59
4	319	136	33	220	109	24	-27	183	110	-104	-85
5	223	87	15	240	81	20	-6	136	159	-72	-61
6	120	34	3	104	30	3	-4	86	74	-31	-27
7	72	19	2	54	17	3	-2	53	36	-17	-15
8	55	15	2	48	14	3	-2	40	34	-13	-11
9	118	26	2	45	17	2	-9	92	28	-24	-15
10	237	58	4	209	53	3	-4	180	156	-54	-50
11	393	145	36	418	149	54	3	248	270	-109	-95
12	215	71	4	205	73	4	3	144	132	-67	-69

4.4 Model Validation

4.4.1 Comparison of WorldClim and ClimGen Precipitation Data

In order to perform correctly, models require accurate input data. Comparing these two different downscaled datasets will provide an indication of the variation caused by the different downscaling method, and therefore assess the validity and uncertainty in the WorldClim downscaled climate dataset provided by WaterWorld. Observed values and projected anomalies were compared for WorldClim and ClimGen. WorldClim outputs were aggregated to 0.5 degree grid cells to make them comparable to ClimGen. Although existing studies have compared alternative downscaling methods, none have specifically compared WorldClim and ClimGen.

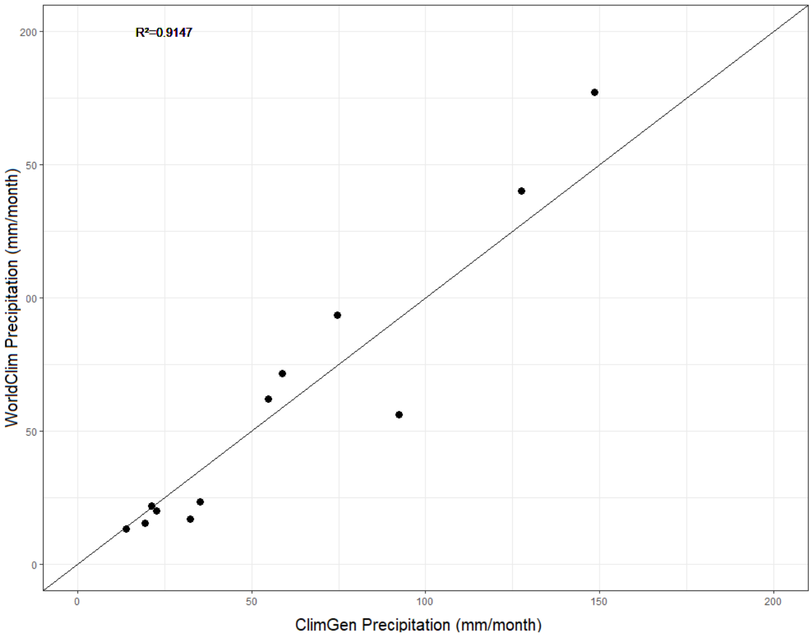

Figure 4-6: Correlation between the WorldClim and ClimGen basin-average precipitation for the WaterWorld baseline period (1950-2000). The line shows y=x, which is where the points would lie if the two datasets were identical.

Figure 4-6 shows the agreement between the monthly mean precipitation values for WorldClim (from WaterWorld) and from the CRU TS database for the same time period (1950-2000) for the basin as a whole. The coefficient of determination value of 0.91 shows that there is good agreement between the two datasets. The two datasets show less agreement in the wet seasons, with WorldClim showing higher values in the months of peak rain fall; April and November.

4.4.2 Evaluation of WaterWorld Precipitation Data with Observations

Exploring the robustness of any modelling conclusions to uncertainties within the models and/or data is an important component of any research project. Precipitation has been argued to be the most significant input for hydrological models, so ensuring accurate input rainfall data is used is paramount for accurate outputs and future projections (Gourley and Vieux, 2006). The performance of hydrological models is frequently reported through a comparison between observed and simulated values (Krause *et al.*, 2005).

In order to evaluate the WaterWorld baseline precipitation, monthly values were compared with observed data from six WMO stations within or close to the basin (data obtained from CRU TS 3). The WMO stations were located at Embu (WMO code: 63720), Meru (63695), Nyeri (63717), Garissa (63723) in the central basin, Lamu (63772) and Malindi (63799) nearer the coast. These locations were shown on Figure 1-4. The monthly averages from the observed data for the period 1950-

2000 were compared to the monthly baseline values in WaterWorld. The WMO observations were converted to mm/month for the purposes of this comparison. The monthly baseline values for these three locations were found using WaterWorld's 'Define Points of Interest' tool, which allows the user to input specific coordinates. WaterWorld provides the output values for the cell that these coordinates are within.

Figure 4-7 shows the results of this comparison. For all locations, graphically there is a good agreement between the observed and the baseline precipitation values. The two datasets for Garissa and Malindi largely follow the same seasonal trend. However, there is some divergence in the months of peaks in rainfall. The two datasets do not agree as strongly for Lamu and Nyeri. Examining these locations also highlights the differences in the months of peak rainfall across the basin. Garissa, Meru, Embu and Nyeri see peak average rainfall in April and November, which corresponds with the basin-average monthly pattern. However, the other locations, Lamu and Malindi, experience a single peak in May. It is likely that these locations are influenced the coastal rainfall.

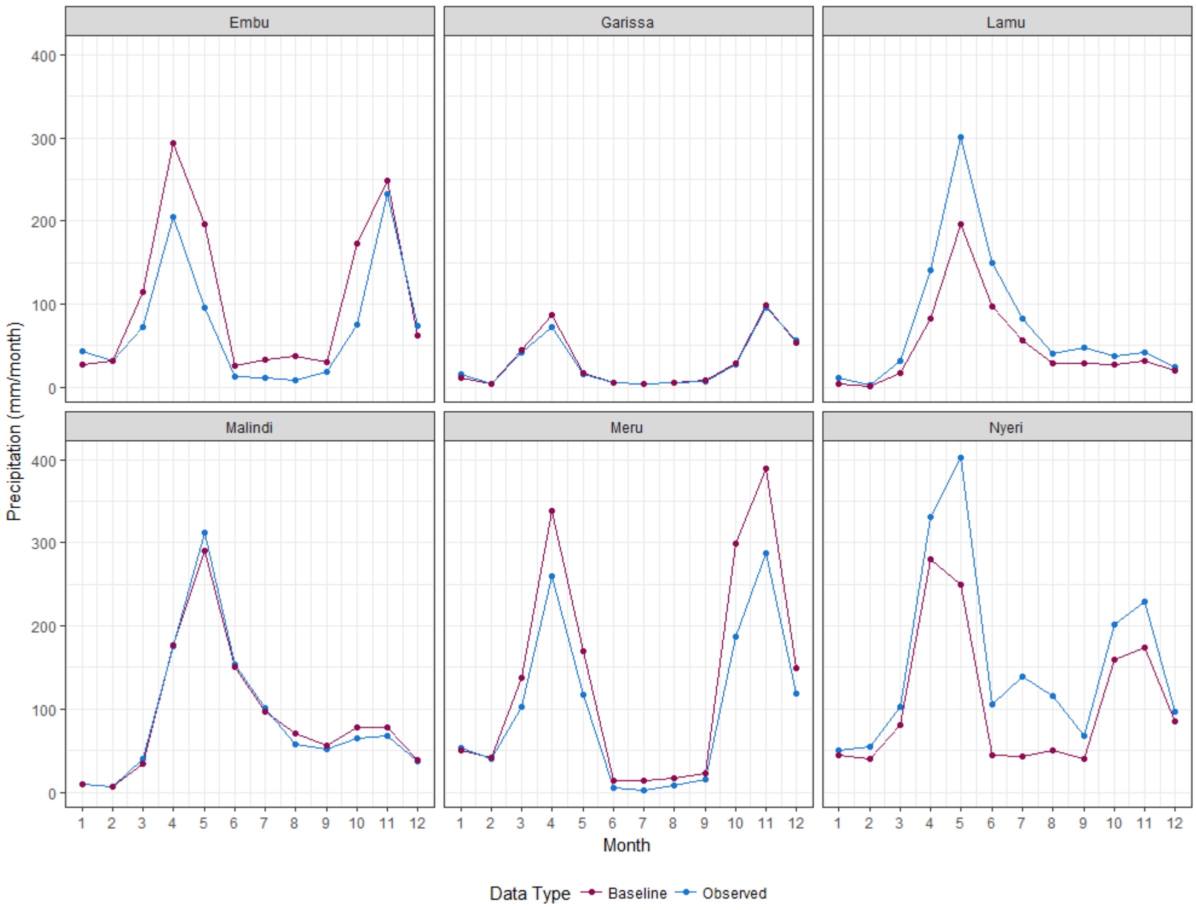

Figure 4-7: Agreement between the observed (CRU TS 3.22, Harris et al., 2014) and baseline (WorldClim) monthly average precipitation for the six WMO stations.

The correlation between the two datasets for all six locations can be seen in Table 4-4. The coefficients of determination for all six locations show strong correlation between the observed and the baseline. The coefficient of determination is a widely used statistical measure in hydrological modelling and evaluation. However, it must be noted that it is strongly affected by extreme values.

Table 4-4: Correlation coefficient for the points of interest within the basin, showing the correlation between the observations and the WorldClim baseline data used in the WaterWorld model.

Location	**Latitude**	**Longitude**	**Elevation (m)**	**R^2 Value**
Garissa	-0.47	39.63	148	0.986
Lamu	-2.3	41	21	0.996
Malindi	-3.2	40	8	0.992
Embu	-0.5	37.45	1350	0.847
Nyeri	-0.5	36.97	1800	0.893
Meru	0.083	40.51	1590	0.984

The WaterWorld model also provides an alternative to WorldClim data for input rainfall. This data is from the Tropical Rainfall Measuring Mission (TRMM 2B31; Kummerow *et al.*, 2000) project. The suitability of the TRMM satellite data was also examined, and it was found that the WorldClim data fit the observations better than the TRMM data. This was clearly seen at the Malindi WMO station (shown in Figure 4-8), where the TRMM data showed peak rainfall values in different months to the WorldClim and observed data. Therefore, the WorldClim rainfall input data has been used to drive WaterWorld.

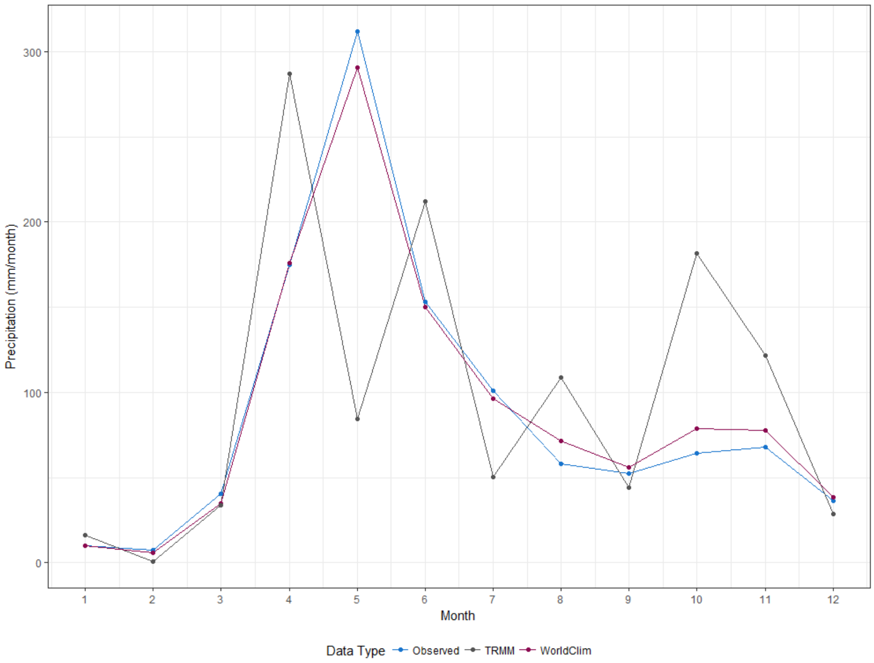

Figure 4-8: Comparison between basin-average 1950-2000 rainfall at Malindi from three sources: Tropical Rainfall Measuring Mission (TRMM) rainfall (Kummerow et al., 2000) shown in grey, WorldClim baseline rainfall (from WaterWorld, 2016) shown in purple and observed rainfall (from CRU TS3.22, Harris et al., 2014) shown in blue.

Overall, it can be said that the WorldClim precipitation data adequately matches the observed values at the monthly scale and can be confidently used in hydrological modelling.

4.4.3 Comparison for Future Changes

As well as comparing the current data for WorldClim and ClimGen, it is possible to compare the anomalies for future projections. Table 4-5 shows the results of comparing the seasonal projected precipitation values for 3 different GCMs for RCP2.6 for the period centred around 2054. It is clear that there are more substantial differences between the individual GCMs than between the different downscaling methods. The range shows the difference between the highest of the three anomaly values and the lowest for each season. This suggests that the downscaling method chosen does not produce as much uncertainty as the individual GCM used. This supports previous research, which has shown that the choice of individual GCM particularly when examining precipitation can significantly change the results (e.g. Beniston *et al.*, 2007). Deque *et al.* (2007) support this, arguing that most uncertainty is due to the individual GCM chosen and emissions scenario rather than the choice of downscaling method. To account for this uncertainty, the ensemble mean is analysed alongside modelling results from individual GCMs.

Table 4-5: Comparison of seasonal projections of basin-average precipitation change (mm/season) for RCP2.6

GCM	Season	Diff (ClimGen-WorldClim)	ClimGen Range of changes between GCMs	WorldClim Range of changes between GCMs
HadGem2ES	MAM	6.41	38.27	53.57
IPS-5l		-8.89		
GISS2r		1.21		
HadGem2ES	JJA	-1.48	-2.27	0.70
IPS-5l		0.62		
GISS2r		-2.29		
HadGem2ES	SON	0.12	8.23	7.78
IPS-5l		-0.92		
GISS2r		1.81		
HadGem2ES	DJF	4.50	19.78	17.98
IPS-5l		6.48		
GISS2r		4.69		

The range of projections between the GCMs is greatest in MAM, where some of the highest rainfall values have been observed. Relatively small variation between the two datasets and three GCMs are seen in JJA. These results are only based on three GCMs, so do not represent the whole range of projections.

4.5 Projected Future Changes

This section will present annual and monthly changes in temperature and precipitation for the Tana River Basin under a range of different climate projections. First, the mean of all available CMIP5 models for each RCP is presented. Then the results of individual GCMs are examined to better show the range of possible future conditions.

4.5.1 Multi-Model Mean - Annual Changes

Due to the range in projections, particularly for precipitation, the mean of all models has been presented first in order to see the general patterns of temperature and precipitation change. For the 2050s, there is an area average temperature increase of between 1.3°C and 2.1°C. This scenario led to an absolute minimum temperature of between 1.6°C (RCP2.6) and 2.1°C (RCP8.5) and maximum of 27.3°C (RCP2.6) and 28.1°C (RCP8.5). Full temperature statistics are presented in Table 4-6. This shows that there is a positive relationship between increasing radiative forcing and rises in temperature in the basin. However, there is still a large variation in mean temperature across the basin, as shown by the spatial standard deviation values which are hardly changed. Increases in the basin-average mean annual temperatures of between 1.3°C and 3.1°C are projected for the 2070s. Using the ensemble mean, it is clear that for three of the four RCPs, the mean annual temperature rise is projected to go beyond the 2°C global temperature threshold ‘target’ by 2070s and only RCP8.5 by the 2050s.

Table 4-6: Basin-average temperature for the 2050s and 2070s using the multi-model mean under the different RCPs. Minimum temperature is the coldest grid cell and maximum is the warmest. The standard deviation is the spatial standard deviation of annual mean temperature across the basin.

Time Horizon	RCP	No. of GCMs	Minimum (°C)	Maximum (°C)	Mean (°C)	Spatial St. Dev. (°C)	Change in mean (°C)
	Baseline (current)		-0.6	26.1	21.3	3.7	-
2050s	RCP 2.6	15	1.6	27.3	22.6	3.6	+1.3
	RCP 4.5	19	1.9	27.7	23.0	3.6	+1.7
	RCP 6.0	12	1.8	27.6	22.9	3.6	+1.6
	RCP 8.5	17	2.2	28.1	23.5	3.6	+2.1
2070s	RCP 2.6	15	2.9	28.0	22.6	3.6	+1.3
	RCP 4.5	19	3.7	28.7	23.4	3.6	+2.1
	RCP 6.0	12	3.7	28.6	23.3	3.6	+2.0
	RCP 8.5	17	4.8	29.6	24.4	3.6	+3.1

It is important to remember that the mean of all available CMIP5 models, although useful, does not represent any individual modelling community’s representation (i.e. the mean does not represent any of the single models). Therefore, it is important to consider the range of projections for the individual models as well. Figure 4-9, showing the projected change in the mean annual precipitation of multi-model mean ± 1 standard deviation across the multi-GCM ensemble (Table 4-1) for both time horizons, goes some way to showing the variability between different model projections. The multi-model mean and the Mean+SD show increases in mean annual precipitation for all RCPs. However, the Mean-SD shows a decrease in rainfall for all RCPs. A similar situation can be seen in the projected changes for the 2070s.

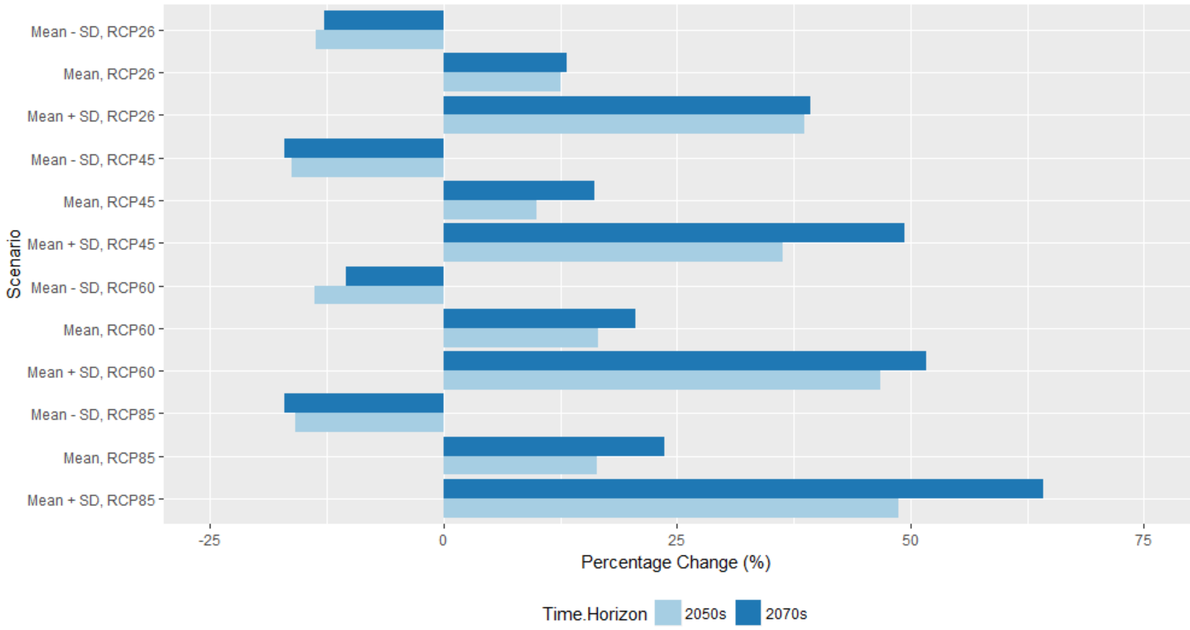

Figure 4-9: Percentage change in annual basin-average precipitation from the baseline for the multi-model mean +- SD. The lighter blue bars show the 2050s and the darker blue bars show the 2070s

The ensemble mean for each RCP shows an increase in mean annual precipitation between the 2050s and 2070s period. However, this increase is small in magnitude compared to the increase from the baseline conditions to the 2050s. For both RCP8.5 and RCP4.5, the Mean-SD scenarios show a decrease in rainfall between 2050s and 2070s.

In addition to the basin-wide mean changes, it is important to consider other scales. The following maps consider changes in precipitation averaged within the district boundaries, which were first presented in Figure 1-4. As decision-making occurs at the district level, understanding average changes and differences between the districts is necessary.

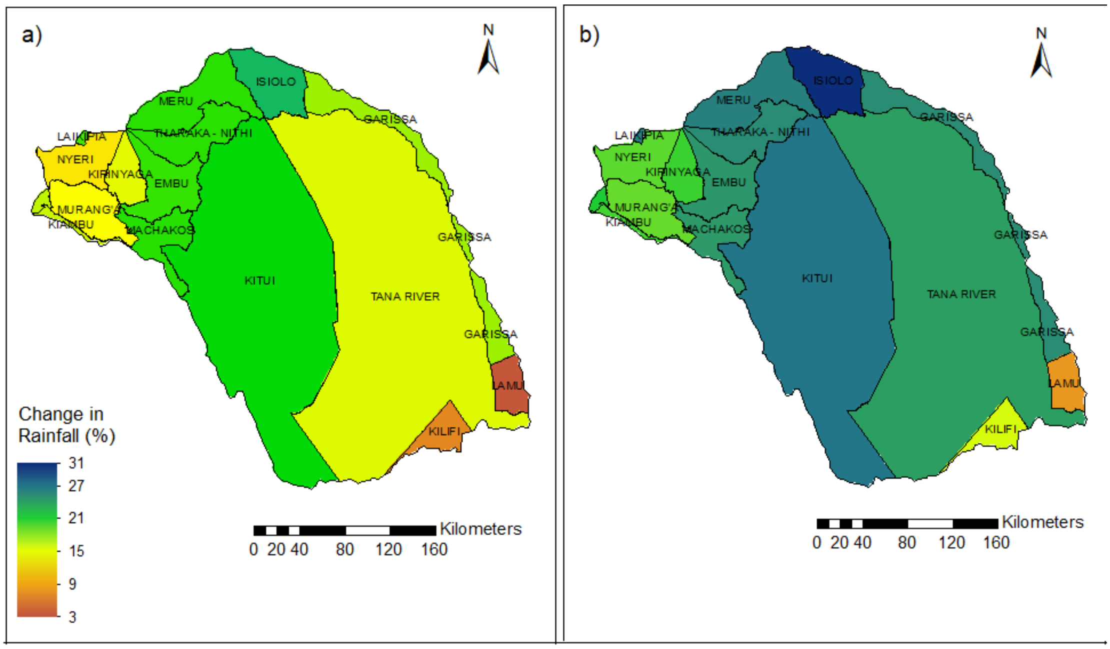

Figure 4-10: Percentage change in precipitation for the RCP8.5 Multi-model Mean scenario, averaged within district boundaries for the two time horizons: (a) 2050s and (b) 2070s.

Figure 4-10 shows the percentage change in annual precipitation averaged over the district boundaries within the Tana River Basin. This figure shows the multi-model mean results for RCP8.5. The percentage changes in rainfall are projected to be higher for the lower basin, particularly for the 2070s. By contrast, the opposite can be said for mean annual temperature. The mean temperature remains extremely low in the mountains in the north of the basin, whereas the floodplains and coastal region see average annual temperatures of around 30°C, up to 3°C warmer than the baseline values.

4.5.2 Individual GCM projections of Annual Mean Change

By examining the full range of GCMs available in WaterWorld for the different RCPs, it becomes clear that there is a large range in the future climate projections for the Tana River Basin. In fact, the GCMs do not all agree on the sign of precipitation change, though nearly all of them project an increase in basin-averaged, annual mean precipitation. Figures 4-11 and 4-12 show the range of basin-mean average annual temperature and total annual rainfall changes for all available GCMs under the four RCP scenarios.

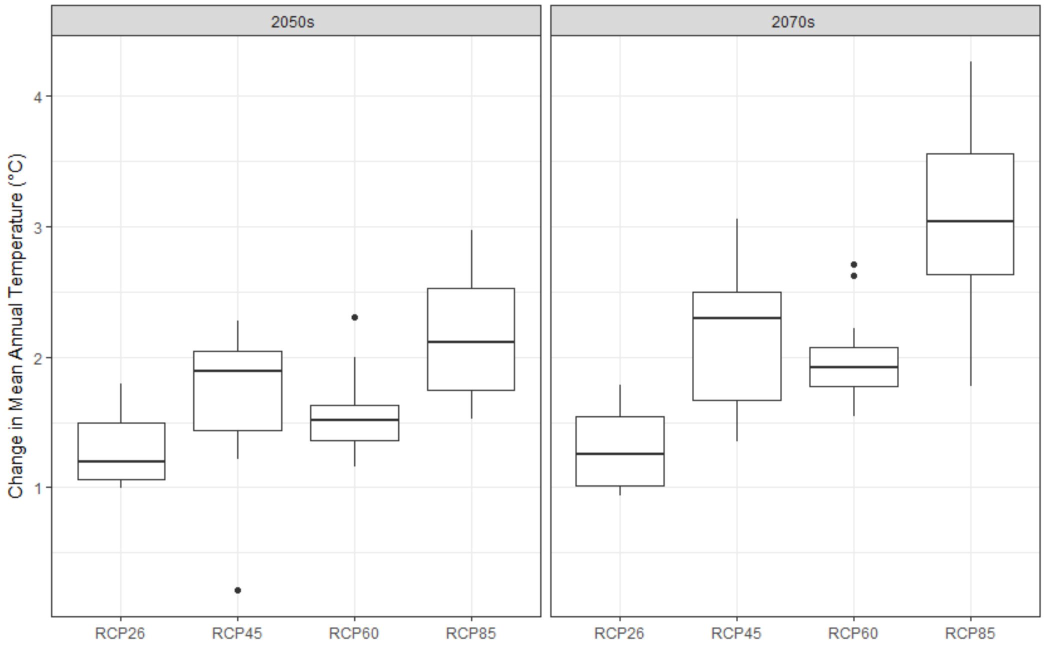

Figure 4-11: Box plots showing the range of basin-mean average annual temperature changes by RCP for (a) 2050s (b) 2070s. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range.

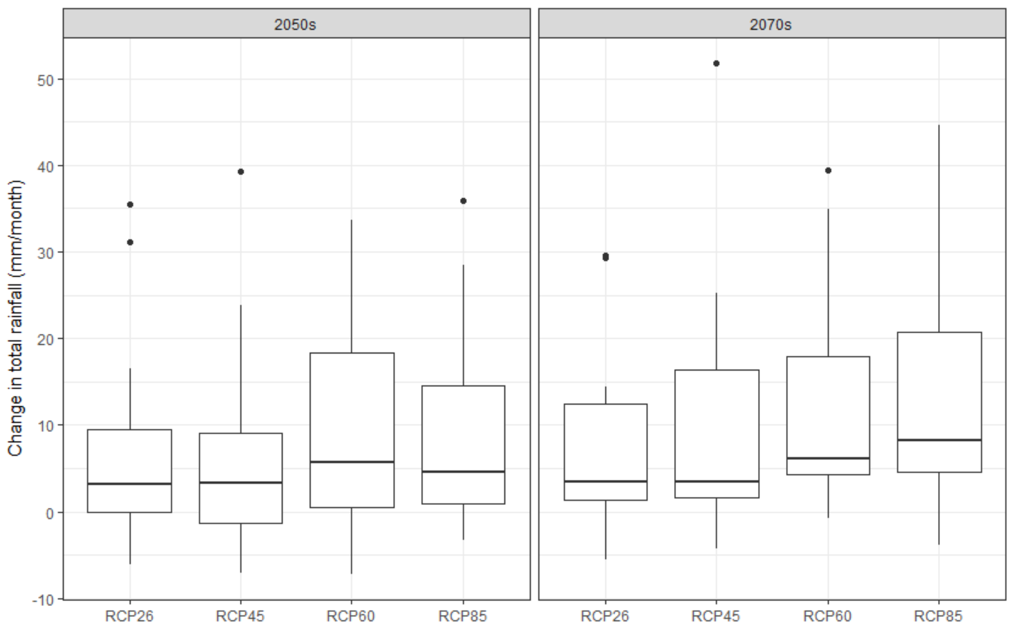

Figure 4-12: Box plots showing the range of basin-mean total annual rainfall changes by RCP for (a) 2050s (b) 2070s Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range.

As shown in Figure 3-14, all models agree on the direction of the temperature trend. Excluding outliers, the models project between a 1°C and 3°C increase in the basin-average temperature by the 2050s. By the 2070s, some GCMs for RCP8.5 project increases of up to 4°C from the baseline conditions. The range of projections for RCP6.0 appears more constrained. However, only 12 GCMs were available for this RCP (see Table 4-1), so it is possible that the more extreme projections are simply missing.

Figure 3-15 shows that the majority of models project wetter mean annual conditions, but disagree markedly on the magnitude of the changes. The median values in the box plots for the 2050s represent about 10-17% increase in average total rainfall (see also Figure 4-9). There is greater variation between the individual GCMs than between the four different RCPs. The outliers, which show increases in rainfall of over 30 mm/month for three of the four RCPs are produced by MIROC-ESM-CHEM. However, this model is also present for RCP6.0 and does not show an exceptionally high value.

For most RCPs and time periods, while the majority of models project wetter conditions across the basin, there is at least one model that projects drier conditions. The models that project drier conditions for over 50% of the Tana Basin for each RCP are presented in Table 4-7.

Table 4-7: GCMs projecting drier annual conditions for at least 50% of the basin

2050s	RCP2.6	GFDL-ESM2G
		MIROC5
		HadGem2ES
		HadGem2-AO
		GFDL-ESM2G
		HadGem2-AO
		HadGem2-CC
		HadGem2ES
	RCP4.5	ACCESS1-0 CSIRO
	RCP6.0	GFDL-ESM2G
		NorESM1-M
	RCP8.5	HadGem2-CC
2070s	RCP2.6	GFDL-ESM2G
		MIROC5
	RCP4.5	NorESM1-M
		HadGem2-CC
	RCP6.0	GFDL-ESM2G
	RCP8.5	HadGem2-AO
		NorESM1-M

The majority of models project wetter conditions in the central basin in the future, but there is more disagreement between the models in the northwest and southeast of the basin. A similar situation is seen for the 2070s. There are no cells in the Tana River Basin where no models project wetter conditions (i.e. where all models project drying) under any of the four RCPs for the two time horizons.

4.5.3 Multi-Model Mean - Monthly Changes

It is also important to examine the monthly changes in precipitation and any changes in seasonality that might occur with climate change. It is not possible to download monthly temperature projections directly from WaterWorld and therefore results are not presented here.

Figure 4-13 shows the percentage change in average monthly rainfall for the four RCPs for the 2050s and 2070s, using the mean of all CMIP5 models. There is a strong agreement between the four RCPs throughout the year. Increases in precipitation are projected for some months, whereas decreases are projected for others. The greatest increases from the baseline are seen in December and January. The greatest variation between the RCPs is also seen in these months. However, it is important to remember that the percentage changes for the multi-model mean do not show the large inter-GCM uncertainty.

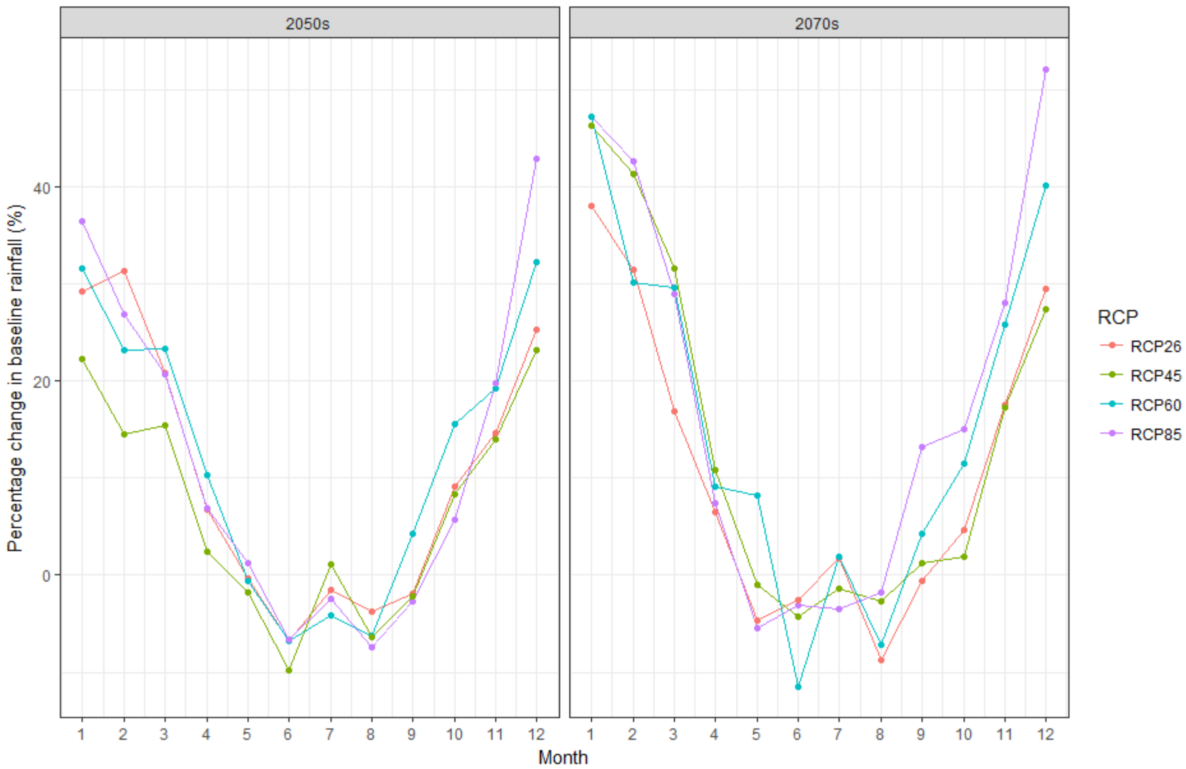

Figure 4-13: Percentage change in mean monthly basin-average rainfall for (a) 2050s and (b) 2070s for the mean of all models for the 4 RCPs

4.5.4 Monthly Rainfall Changes for Points of Interest within the Tana Basin

So far, the majority of results have been presented as basin-wide averages. However, as previously stated, precipitation varies greatly throughout the basin. The projections for specific points within the basin have also been examined by extracting the grid cell that contains their co-ordinates using WaterWorld's Points of Interest (POI) tool. Figure 4-14 shows the percentage change in mean monthly precipitation at four POIs for the four multi-model mean scenarios for the 2050s. Generally, the 4 POIs show a similar temporal pattern of change to the basin-average changes shown in Figure 4-13.

Embu is likely to experience wetter conditions in most months. There is a general agreement between the four radiative forcing scenarios here for the majority of months. One notable exception is December, where the four RCPs vary greatly on the predicted percentage change – from between 0.3% for RCP6.0 and 46% for RCP8.5. Increases in rainfall at Garissa occur in the rainy seasons: March-May and October-December. These changes range from between 11 and 40% between October and December, and 5 and 30% for March-May. Additionally, increases can be seen in the January-February dry season. Although large percentage changes are seen in these two months, it is important to remember that the baseline rainfall here is extremely low. By contrast, decreases in precipitation are projected for all four radiative forcing scenarios for at least some months in the other dry season (June to September). An exception is the increase of around 5% projected for July by the RCP4.5 multi-model mean. Contrastingly, Meru may experience much drier conditions for much of the year. Decreases in precipitation are projected between April and October. The largest decreases (of around 30% less rainfall) are seen in June.

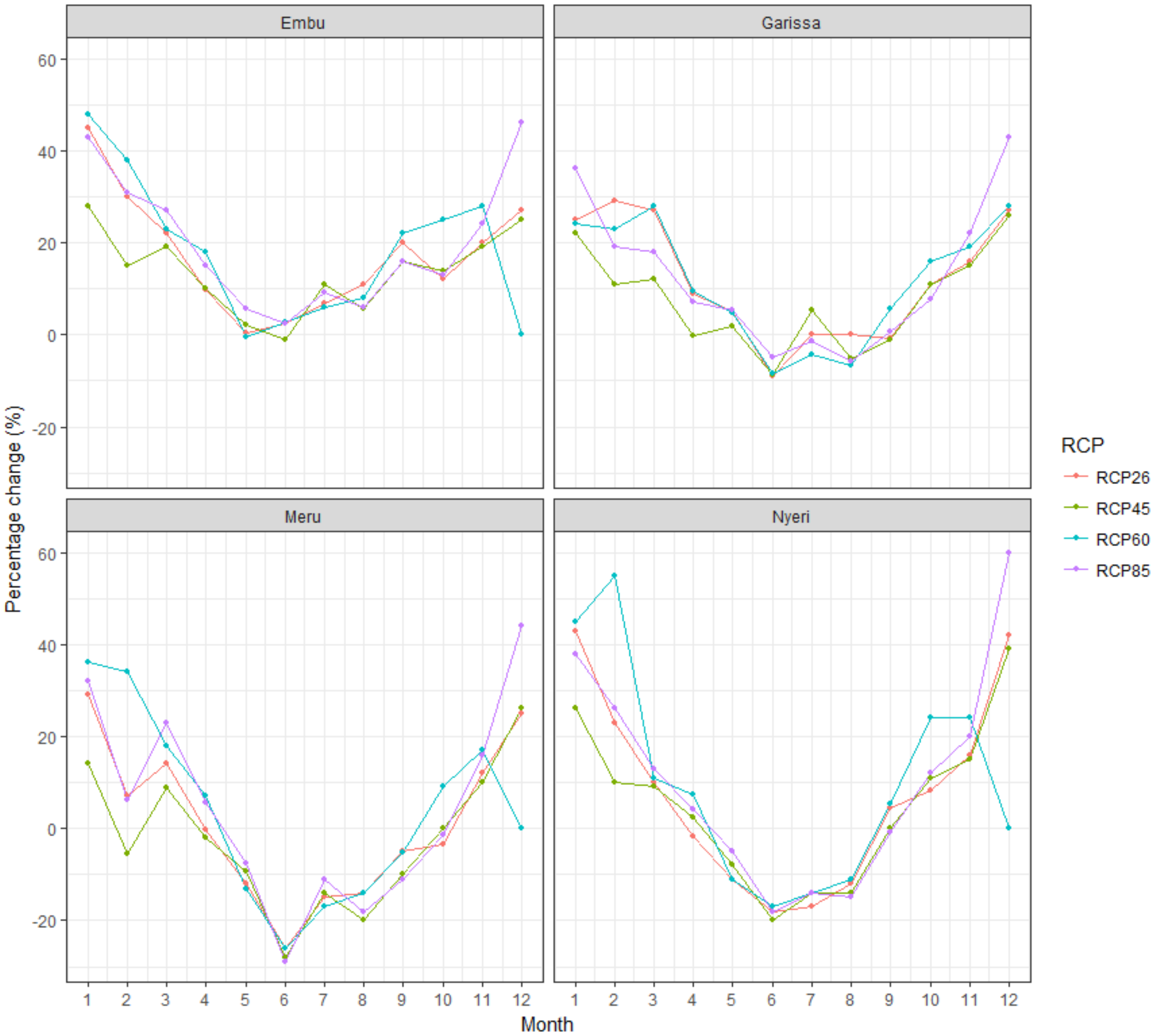

Figure 4-14: Percentage change in mean monthly precipitation for the four multi-model mean scenarios for the Embu, Garissa, Meru and Nyeri stations for the 2050s

4.5.5 Individual GCM projections of Monthly Precipitation Changes

As seen with annual changes in Section 4.5.2, the individual GCMs show a large range of projections for monthly precipitation change. Figure 4-15 shows the climate change scenario dependence of projected change in monthly precipitation between the baseline and the 2050s.

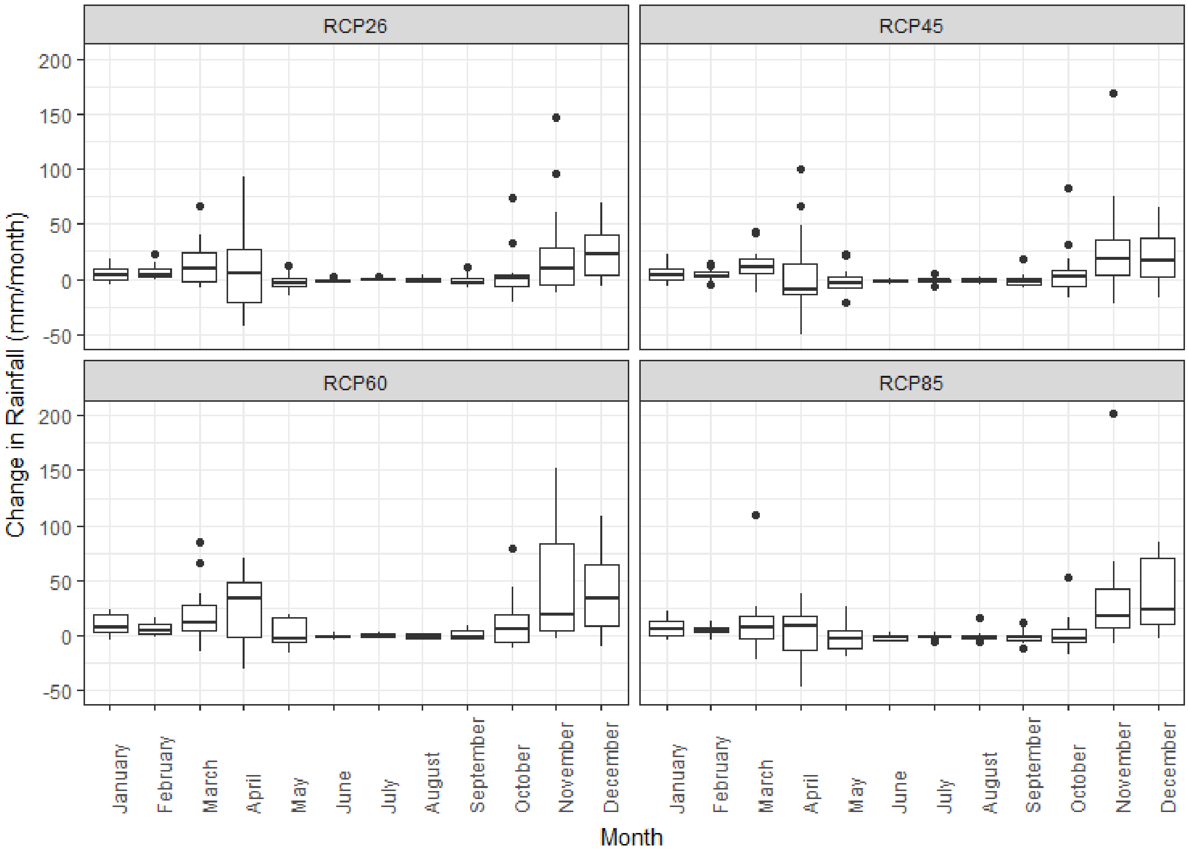

Figure 4-15: Monthly change in basin-average mean precipitation for 2050s for the four RCPs. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range.

As seen at the individual points of interest examined above, at the basin-scale, rainy seasons are projected to become wetter but the largest variation between the individual models, and so the largest uncertainty, is in the wettest months: April and November. The individual models show a stronger agreement in the dry months. This is seen in all 4 RCPs. The same is shown for the 2070s on Figure 4-16.

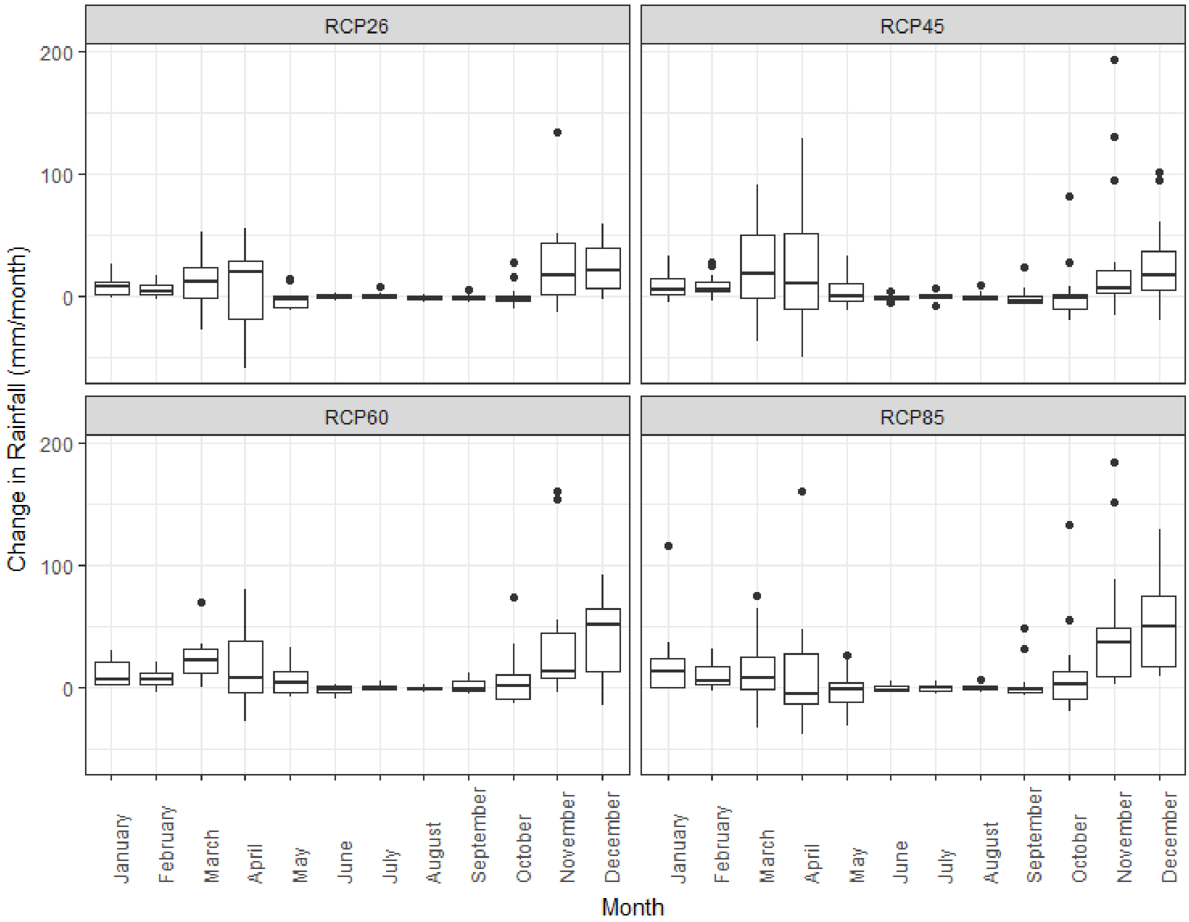

Figure 4-16: Monthly change in basin-average mean precipitation for 2070s for the four RCPs. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range.

4.6 Discussion

Results clearly show that projected climate change across a wide range of scenarios generally leads to a warmer Tana River Basin, with increased precipitation. Projected temperature changes show a stronger agreement than changes in precipitation, chiefly that warming will continue in the Tana River Basin throughout the century, except for RCP2.6 where warming levels off mid-century. Average temperature has been shown to increase with higher radiative forcing. Average predicted changes in precipitation do not vary greatly between the RCPs. However, there are large discrepancies between the individual GCMs and they do not even agree on the sign of precipitation change for the area, though nearly all of them project an increase in basin-averaged, annual mean precipitation. It is not possible to assign likelihoods to the range of the projections. A large variability in GCM projections has already been demonstrated by other research focusing on water resources and water security across Africa (Conway *et al.*, 2007; Shongwe *et al.*, 2011; Farazmarzi *et al.*, 2013; Aich *et al.*, 2014; Kent *et al.*, 2015). The disagreement between the individual GCMs may have several underlying causes, which has already been discussed to some extent earlier in this chapter and in the Literature Review. Differences in spatial and temporal resolution between the models is a major factor. Buytaert *et al.* (2010) argues that the coarse resolution of the GCMs cannot take into account the effect of local elevation changes and orographic rainfall. Additionally, biases in climate models may lead them to inaccurately represent the two rainy seasons in East Africa (Yang *et al.*, 2014). This may lead to GCMs projecting wetter future conditions, while the observations show that the area has become drier. There is a significant amount of work on how GCMs may misrepresent the rains in East Africa (Yang *et al.*, 2015; Dunning *et al.*, 2017; Hirons and Turner, 2018), with the difference between the drying trend and the projected wetting becoming known as the East African paradox (Rowell *et al.*, 2015).

However, these results also show that the magnitude of changes between the 2050s and 2070s are minor compared to those seen between the baseline and 2050s. This serves as a justification for a greater focus on the 2050s in the following chapters.

These results contrast with the evidence of drying shown in Kenya in recent years (Met Office, 2011). These observations of drying were discussed in Section 3.1. This further demonstrates that projections of precipitation change are still associated with a large amount of uncertainty. Global climate models cannot provide reliable projections of the size of precipitation change on a local scale, which is necessary for effective water resources management to be planned and implemented (Buytaert *et al.*, 2010). Uncertainty between the different projections and within the GCMs must be stated and management decisions must be made in the face of this uncertainty.

Significant percentage changes can be seen at the individual points of interest defined within the basin, such as Embu and Meru in the upper Tana basin and Garissa on the lower lying floodplain. This may have important implications for county-level management and adaptation.

Rainfall and therefore runoff and river flow are extremely seasonal and could increase most in the wet seasons, so it’s important to consider the extremes: flooding may increase in the rainy seasons as a result of more intense rainfall whereas droughts may continue in the drier months and may become more intense as average temperatures rise. Few *et al.* (2015) show that the recent increase in frequency of droughts in Kenya has affected people's ability to maintain food security or cope with crop failures. The lack of precipitation increases projected for the dry months suggest that this problem will continue into the future; further reducing food security and limiting poor people's ability to adapt to the changing climate. Improvements in water storage and conservation may be necessary, particularly if rainfall increases markedly in the rainy seasons. Rainfall in Kenya experiences large inter-annual variations (Hastenrath *et al.*, 2007), but the WaterWorld model does not allow for an analysis of inter-annual variability; highlighting one of the limitations of this study.

4.6.1 Implications for Policy and Management

Even though the majority of models predict wetter conditions, increases in water supply may not be enough to cover increases in predicted water demand. In their National Water Master Plan 2030, the Government of Kenya predict water demand will increase to around 700% of the 2010 value by 2030. Therefore, these projected increases in precipitation will not adequately account for the increases in demand caused by population growth and the country's development.

Rainfall is the most important part of East Africa's climate system, both economically and socially (Oloo, 2014). Therefore, the uncertainties in the projections are likely to have important implications for policy. Rain-fed agriculture still accounts for over 50% of food production in Africa (Faramarzi *et al.*, 2013) and agriculture in Kenya accounts for around 25% of GDP (Ndung'u and Otieno, 2009). The Vision 2030 development agenda includes an economic flagship project called the Tana River Basin Development Scheme, which aims to increase agriculture in the region (GoK, 2008). Although irrigated agriculture is a policy priority for alleviating poverty in Kenya, there are a number of factors limiting its development, including policy objectives and upstream-downstream trade-offs. However, reducing rain-fed agriculture and instead focusing on irrigation potential could also lead to problems. As stated by Adimo *et al.* (2012), policies for adaptation to climate change must be both holistic and flexible to avoid an overreliance on irrigation in a future where water resources may actually decrease.

Some GCMs suggest that the climate could become wetter and then drier further into the future. Non-monotonic predictions of rainfall changes have been seen in other areas, for example in South America (Hawkins *et al.*, 2014). This may have important implications, as adapting for a wetter climate in the shorter term may lead to maladaptation if the climate becomes drier in the longer term. This will affect long-term climate policy. In addition, non-monotonic changes may have important implications for other sectors, including biodiversity protection. If these types of changes occur, decision-makers should be aware that near-term changes may need to be reversed in the longer term (Hawkins *et al.*, 2014). This also highlights a potential problem with the pattern-scaling method of downscaling used for the ClimGen projections, as it is based on the assumption of linear behaviour (Herger *et al.*, 2015).

4.7 Chapter Summary

This chapter discussed the baseline and changes to the climate of the Tana River Basin. CMIP5 models were used to characterise the temperature and precipitation changes projected to occur in the basin under the four emissions scenarios. The baseline conditions were found to correctly represent the monthly cycle of precipitation, but the peaks in both the long and short rains were overestimated by the WorldClim baseline. This is consistent with previous work which found that the CMIP5 models overestimate East African rainfall. Overall, the models agree on the upward direction of the temperature trend but more uncertainty is seen in changes in precipitation. Increases in mean annual rainfall are projected by the ensemble mean for the four different RCPs, but some individual GCMs project drier future conditions. This variation in GCM projections has already been noted in other modelling work focussing on Africa. Finally, the uncertainty in CMIP5 GCM outputs has also been shown; particularly by the large variation in anomalies of projected precipitation. This uncertainty may necessitate policies aimed at encouraging flexibility and building adaptive capacity, to ensure a range of future precipitation changes can be accommodated.

The following chapter examines the change in hydrological variables (namely runoff, evapotranspiration, water balance and water stress) using the WaterWorld model for the same future periods and discusses the implications of these changes for climate change adaptation and future water management.

Chapter 5 Current Hydrological Conditions and Future Projections

5.1 Introduction

Natural ecosystems and societies rely on water in a large variety of ways, so it is important to investigate possible changes to freshwater resources with climate change. This chapter will present results from the WaterWorld model to address Objective Ia. This chapter will focus on annual and monthly changes in water balance and water stress, as well as actual evapotranspiration (AET). First, the chapter describes the model. The baseline conditions are described in Section 3. Then, Section 4 presents the results of a range of climate change scenarios (addressing Objective IV) and Section 5 discusses the implications and limitations of these results.

5.2 Methods: Hydrological Modelling

5.2.1 Model Selection

Hydrological models that have previously been applied to Kenya include: the Soil and Water Assessment Tool (SWAT; by Jacobs *et al.*, 2007; Sood *et al.*, 2017); the Stream Flow Model (SFM; Mutua and Klik (2007)) and HEC-HMS (Olang and Furst, 2011). The main features of these models, as well as the key strengths and weaknesses is provided in Table 5-1.

Table 5-1: Review of a selection of hydrological models that have previously been applied in Kenya

Model	Developed by	Spatial presentation	Process presentation	Data Requirements
HEC-HMS Hydrological Modelling System	USACE (2000)	Semi-distributed	Physically-based	Land-use, soil group, flow records, topography map, land-use maps and rainfall
SWAT Soil and Water Assessment Tool	Arnold *et al.* (1993)	Semi-distributed (HRUs)	Physically-based	Precipitation, temperature, solar radiation, wind speed, PET, land cover, elevation.
FEWS-NET GeoSFM Geospatial Stream Flow Model	Artan *et al.* (2002)	Semi-distributed (sub-watersheds)	Physically-based	Precipitation, evapotranspiration, topography, soil, and land cover

Olang and Furst (2011) analysed the effects of historical land cover changes on river flows and flood peaks in Kenya's Nyando Basin using the HEC-HMS model. They found that past changes in land cover had increased peak flows in the river, with greater impacts being felt in upstream areas. However, the authors noted problems of data availability as limitations with the results. Mutua and Klik (2007) used the SFM to predict daily streamflow in Kenya's ungauged Masinga catchment. The simulated results adequately represented streamflow and soil moisture conditions, as well as the variability in conditions across the catchment. However, the model overpredicted daily streamflow during the wet seasons and overestimated streamflow in the dry season. Mutua and Klik (2007) concluded that the model was useful but that additional data collection and model calibration was required. By contrast, Jacobs *et al.* (2007) applied the SWAT model to the Upper Tana River Basin to determine the effects of reforesting the area. Results showed that reforestation would siginificantly reduce the volume of sediment entering into the Masinga dam. More recently, Sood *et al.* (2017) used the SWAT model to project the impacts of climate change to the Tana River Basin. Their results projected increases in streamflow in the future, as discussed in Chapter 2, Section 7.

For this study, the previously applied hydrological models discussed in Table 5-1 could not be used as recent discharge data could not be obtained. Only observed discharge data for the gauging station at Garissa for the period 1934-1975 is available from the Global Monthly River Discharge Data Set (RivDIS; Vorosmarty *et al.* (1998)). More recent data and data for other gauging stations must be obtained in person from the Water Resources Management Authority (WRMA) in Kenya. Collecting the data in this way was not possible for this study. Therefore, the WaterWorld Policy Support System (PSS) model (Mulligan, 2013b) was chosen to examine the impacts of a range of possible climate futures on hydrology. WaterWorld was originally developed as the FIESTA (Fog Interception for the Enhancement of Streamflow in Tropical Areas; Mulligan and Burke, 2005) model for use in cloud forests in tropical mountainous regions. WaterWorld is predominantly a water balance model (Mulligan, 2013b).

Practically, all of the data required to run simulations is provided in WaterWorld, which means it can be applied to areas where data is scarce or of low quality. The WaterWorld PSS is freely available online and produces a range of output maps and statistics, allowing for a large variety of research topics. Moreover, the

WaterWorld model does not require calibration with observed values and hence can be employed in ungauged basins. Calibration is not possible in these situations (Sivapalan, 2003). WaterWorld may not be more suitable than the other hydrological models previously applied to the region but provides a useful compromise when observed discharge and other necessary input data cannot be accessed.

5.2.2 WaterWorld: Model Description and Structure

Policy support systems (PSSs) combine models of environmental processes with geospatial data to examine the baseline (current) conditions and the impacts of future scenarios or policy interventions (Mulligan, 2016). They are an extension of decision support systems (DSSs). However, while DSSs are designed to aid decision-making around a specific problem, PSSs examine a broader range of policy options. WaterWorld (Mulligan, 2013b; available at: http://www.policysupport.org/) is an example of a PSS. It is a fully-distributed, process-based hydrological tool designed to explore the consequences of different policy options before they are implemented (Mulligan and Burke, 2005). Here, the model is run at 1km^2 resolution. WaterWorld can be utilised in data-poor environments and ungauged river basins, which is particularly useful for Kenya, where the river basins are large but gauging stations are extremely limited.

As WaterWorld was originally developed as the FIESTA (Mulligan and Burke, 2005) model, the model calculates the contribution of fog inputs to water balance. The FIESTA-delivery model is still an integral part of the WaterWorld model. Despite being originally developed for cloud forests, the model has been widely used in Africa and Asia (Mulligan, 2013b) and has been shown to be suitable for other regions. Mulligan (2015) coupled the WaterWorld model with a database for commodity flows to examine the effect of climate change on commodities that originate from Africa's drylands and their supply chains. Results of this study found that projected increases in rainfall could positively benefit supply chains but that the specific changes will vary between the different commodities. Mulligan (2016) used WaterWorld to examine recent and future risks of land degradation in Africa from land use and climate change. Other previous applications of WaterWorld include modelling changes in evapotranspiration with future growth in cropland (Pandeya and Mulligan, 2013) and examining a range of threats to water security in the Amazon (van Soesbergen and Mulligan, 2014). WaterWorld can be used to model land and water management approaches and land cover changes as well as possible climate futures, making it relevant to policy work.

WaterWorld uses the hydrological baseline 1950-2000 and land cover for the year 2000. Figure 5-1 shows the key components and fluxes simulated in the WaterWorld model. The fluxes are simulated within each of the grid cells within the modelled area. The factors influencing fog inputs to both pasture and forest are shown.

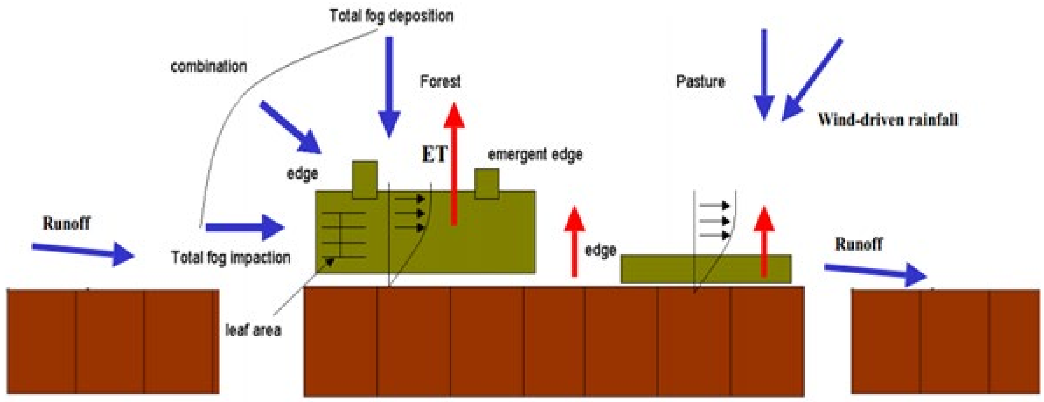

Figure 5-1: Key components of the WaterWorld model (from Mulligan and Burke, 2005).

5.2.2.1 The SimTerra Database

The SimTerra database (Mulligan, 2013a) is the primary source of all major spatial datasets of hydroclimatic and environmental properties that are used in WaterWorld. The key input datasets are listed in Table 5-2. The database consists of the best available global datasets, which have been generated from ground-based or remote sensing sources. Major datasets from SimTerra used in WaterWorld include: WorldClim climatology (Hijmans *et al.*, 2005), wind speed (New *et al.*, 2002), cloud climatology (Mulligan, 2006a), terrain (Farr and Kobrick, 2000), and land cover from Landsat-based vegetation continuous fields (Sexton *et al.*, 2013). In addition to reprocessed datasets, the database also includes some new datasets, such as the global dams database.

In terms of climatology, datasets of about 1-km spatial resolution from the 'WorldClim' (Hijmans *et al.*, 2005) database were compiled for the database. This data covers monthly precipitation and mean, minimum and maximum temperature for the baseline period of 1950 to 2000. WorldClim was described in the detail in the previous chapter.

Cloud-related datasets derived from the MODIS MOD35 Cloud Mask Product are used by WaterWorld to calculate solar radiation (Mulligan, 2006b). The topographic dataset included in the SimTerra database is the SRTM DEM (Farr and Kobrick, 2000). This is a 1km continuous raster dataset. Topographic datasets are important in hydrological modelling as they are used to extract information about slope, aspect and drainage networks.

Model calculations are carried out for one year, using a long term (the average of 1950-2000) climatology. During a simulation, WaterWorld simulates four diurnal time steps (at 00:00-06:00 hrs, 06:00-12:00 hrs, 12:00-18:00 hrs and 18:00-24:00 hrs). These represent the mean diurnal cycle for each of 12 monthly time steps. Therefore, a total of 48 time steps occur in a complete simulation. This representation of the diurnal cycle is important for processes such as cloud water interception (CWI) and ET (Mulligan and Burke, 2005).

Table 5-2: Key input data provided by the WaterWorld model

Parameter	Units	Source
Boundary layer wind direction (monthly)	Degrees from N	Derived from BADC (2004)
Mean sea level pressure (monthly)	mb	Derived from BADC (2004)
Elevation (SRTM)	Meters	Farr and Kobrick (2000)
Air temperature (monthly)	°C x 10	New *et al.* (2003)
Wind speed (monthly)	m/s	New *et al.* (2003)
Relative humidity (monthly)	%	New *et al.* (2003)
Mean annual temperature	°C	Hijmans *et al.* (2005)
Mean monthly precipitation (monthly)	mm/month	Hijmans *et al.* (2005)
Total annual precipitation	mm/year	Hijmans *et al.* (2005)
Mean daily maximum temperature (monthly)	°C x 10	Hijmans *et al.* (2005)
Mean monthly temperature (monthly)	°C x 10	Hijmans *et al.* (2005)
Mean daily minimum temperature (monthly)	°C x 10	Hijmans *et al.* (2005)
Cloud frequency (DJF)	Fraction	Mulligan (2006)
Cloud frequency (JJA)	Fraction	Mulligan (2006)
Cloud frequency (MAM)	Fraction	Mulligan (2006)
Cloud frequency (SON)	Fraction	Mulligan (2006)
Mean annual cloud frequency	Fraction	Mulligan (2006)
Cloud frequency (monthly)	Fraction	Mulligan (2006)
Cloud frequency 00:00-06:00 hrs	Fraction	Mulligan (2006)
Cloud frequency 12:00-18:00 hrs	Fraction	Mulligan (2006)
Cloud frequency 18:00-24:00 hrs	Fraction	Mulligan (2006)
Cloud frequency 06:00-12:00 hrs	Fraction	Mulligan (2006)
Local drainage direction	Direction	Mulligan (2011)
Cover of bare ground	Percentage	Hansen *et al.* (2006)
Cover of herb-covered ground	Percentage	Hansen *et al.* (2006)
Cover of tree-covered ground	Percentage	Hansen *et al.* (2006)
Daily temperature range (monthly)	°C x 10	Hansen *et al.* (2006)

:

WaterWorld produces over 60 mapped output variables, both at annual and monthly timescale which can be downloaded for use with GIS software. Various time slices for individual points or for the whole area of interest are also simulated by the model and can be visualised or downloaded (Mulligan, 2013b). Given the lack of global data, WaterWorld does not simulate flows in soil and groundwater

(Mulligan and Burke, 2005). The key outputs from WaterWorld considered in this research are presented in Table 5-3.

Table 5-3: Key outputs from WaterWorld used in this research

Output	Units	Description
Local water balance	mm/month	Rainfall, fog inputs and, where relevant, snow minus actual evapotranspiration (AET). Where water balance is negative local AET is supported by upstream sources of water and/or groundwater. Calculation show in Equation 2.
Runoff (at Garissa)	mm/month	Calculated as water balance cumulated downstream.
AET	mm/month	Actual evapotranspiration, calculated as shown in Equation 3 below.
Average annual water stress	%	% of water demand unavailable or contaminated, averaged across the year.

5.2.2.2 Key Calculations within WaterWorld

Originally, the FIESTA-delivery model was designed to provide estimates of fog interception (Mulligan and Burke, 2005). Fog inputs are calculated from wind speed, vegetation (tree and herbaceous cover) and topographical data. Vegetation types are based on MODIS vegetation data (Hansen *et al.*, 2006). Fog incidence is calculated as a function of the observed frequency of observed atmospheric cloud and the tendency for condensing conditions to land exist at the surface. Therefore, total fog interception is the sum of vertical deposition and horizontal impaction, as shown in Equation 1.

$$\text{Fog Interception} = \text{Air Flux } \times \text{LWC } \times \text{Interception efficiency } \times \text{Area exposed}$$

Equation 1

Where Air Flux = the flux of air past an intercepting surface, LWC = the liquid water content of the moving air, Interception efficiency = the capacity of the vegetation to trap water particles by deposition and impaction and Area exposed = the area of vegetation exposed to the depositing and impacting fluxes.

WaterWorld also calculates potential evapotranspiration, based on the net radiation received and the surface area available for transpiration and wet canopy evaporation (Mulligan, 2013b), as shown in Equation 2. The evapotranspiration model is a simple energy driven model which used Leaf Area Index (LAI) as a proxy for the availability of water through stomata. Other than LAI, the model takes little account of vegetation properties. Therefore, one assumption in the WaterWorld model is that this measure is a good enough substitute for availability of water through stomata.

$$Ea = \frac{611 \times \exp\left(\frac{17.27 \times \mathrm{NT}}{273.15 + \mathrm{NT}}\right)}{1000}$$

$$SSCK = \frac{4098 \times Ea}{\sqrt{273.15 + NT}}$$

$$PotE = \left(\frac{SSCK}{SSCK + 0.066}\right) \times NWM$$

$$PotE = PotE \times (60 \times 60/1000000)$$

$$PotE > 0: PotE = \left(\frac{PotE}{2.45}\right); PotE \leq 0; PotE = 0;$$

$$PotE > 0: ActE = PotE \times ETFrac; PotE <= 0; ActE = 0$$

Equation 2

Where NT = air temperature (°C), Ea = vapour pressure (KPa), SSCK – slope of the saturation vapour pressure curve (Kpa/C), NWM = Net radiation receipt (W/m2), 2.45 = latent heat of vaporisation of water (MJ/kg).

Water balance (or budget as shown in Equation 3) is calculated by adding precipitation and fog inputs together and subtracting actual evapotranspiration (AET). The water balance is calculated for every pixel and then cumulated downstream, using the stream network to determine runoff values. Water balance is calculated using the equation below (from Mulligan, 2013b). First, precipitation is converted from mm/month to mm/hr and the water balance (budget or runoff within one pixel) is calculated as:

$$\mathrm{Budget} = \left((\mathrm{PR_{mm}} + \mathrm{FINT\_mm}) - \mathrm{ActE}\right)$$

Equation 3

Where PRmm is precipitation in mm, FINT_mm is the total potential cloud interception (mm) and ActE is actual evapotranspiration.

No soil moisture, groundwater or canopy water balance are produced (Mulligan and Burke, 2005). The model assumes that, if water balance decreases, the groundwater reserves will also decrease in the long term. Agricultural demand is incorporated in the water balance because water balance includes AET, which is derived from the current land cover and land use, including the effects of irrigation).

In WaterWorld, runoff is calculated as water balance cumulated downstream. Runoff is approximated by routing the water balance down a stream flow network giving an indication of potential long-term runoff with soil and groundwater stores in equilibrium. WaterWorld is predominantly a water balance model (Mulligan, 2013b).

The change in the average annual water stress index will also be examined. The water stress index is the percentage of blue water (non-agricultural water) demand which is not supplied, based on supply and demand. WaterWorld calculates the water supply as the simulated water balance, which includes agricultural water demand. The demand is calculated as the population multiplied by per capita domestic and industrial demand. Both supply and demand are calculated by month and then averaged over the year (Mulligan, 2013b). The WaterWorld water stress index does not include any water storage (for example in reservoirs and groundwater stores) and so does not consider water surpluses in some months may offset the lack of water supply in the following months. Additional WaterWorld equations and model documentation is provided in Appendix II.

5.2.2.3 Model Set Up

As WaterWorld contains the data necessary to run the model for anywhere in the world, the set up process is quick and straightforward. The general processes in WaterWorld are described in Figure 5-2.

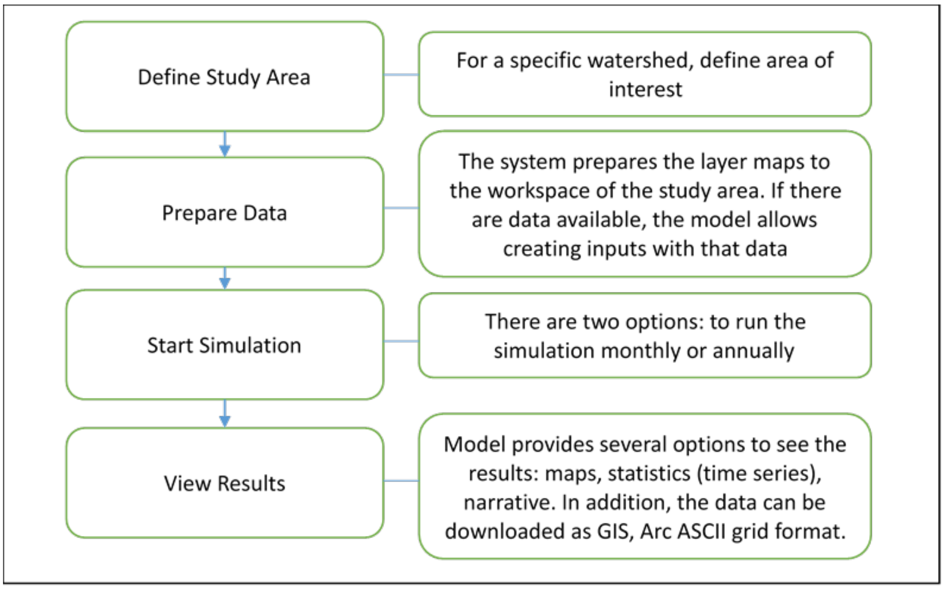

Figure 5-2: Key stages in WaterWorld Model running (adapted from Mulligan, 2013b)

The first step involved with running WaterWorld is to define the study area. WaterWorld includes a list of pre-defined large basins, so for this research, the large East Central Coast Basin was defined as the study area and then the Tana Basin was chosen as an 'area of interest' within that basin. The outline of the East Central Coast Basin and the location of the Tana River Basin within it can be seen in Figure 5-3. The outlet point for the watershed has been defined as -2.522 latitude, 40.507 longitude, using WaterWorld's 'Define points of interest' tool.

To run the baseline, all of the input data is provided by WaterWorld. However, the option to upload alternative input data is given. As high quality, easily available datasets are scarce for Kenya, the input data provided by WaterWorld was used in this research. Once the study area has been chosen, the model will prepare the data and a baseline scenario can be run.

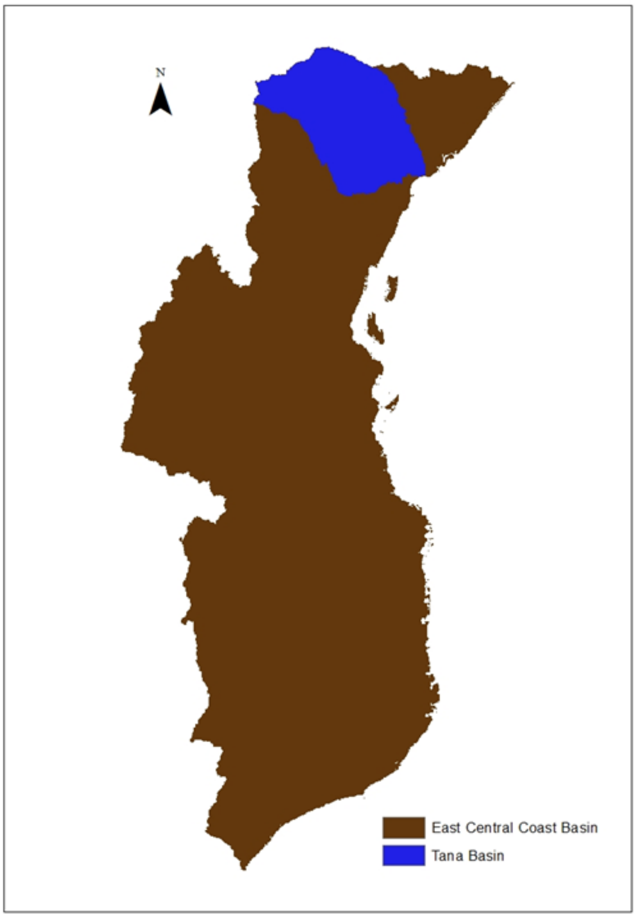

Figure 5-3: Outline of the East Central Coast and Tana River Basins from WaterWorld

Once a baseline simulation has been run, it is possible to run climate change scenarios for each of the CMIP5 GCMs listed in Table 3-1. As well as running each of the GCMs individually, it is possible to run an ensemble mean of the available GCMs. This is a way of reducing the potential bias associated with choosing a single GCM, considering the uncertainty between different GCM projections. Annual and monthly output maps were produced and analysed.

5.3 Baseline Conditions

This section examines the hydrological characteristics of the Tana River Basin, using the baseline conditions from the WaterWorld model, which were already presented for temperature and precipitation (and compared to observation data) in Chapter 3.

5.3.1 Annual Conditions

Hydroclimate variables are highly variable within the study region. The annual hydrological properties are presented in the Table 5-4.

Table 5-4: Hydrological properties of the Tana River Basin for the baseline conditions. The standard deviation is the spatial standard deviation across the basin.

	Rainfall (mm/month)	AET (mm/month)	Water Balance (mm/month)	Fog Deposition (mm/month)	Fog inputs as a percentage of water balance (%)
Min	0.0	5.6	-122.2	0	0
Max	225.9	121.7	207.7	6.1	14.6
Mean	59.5	73.1	-12.7	0.6	3.4
Spatial SD	27.2	13.6	39.6	1.2	2.2

The mean annual rainfall from WaterWorld is 59.5 mm/month. Rainfall has been examined in more detail in Chapter 3. The basin-average annual water balance is -12.7 mm/month and the average AET is 73.1 mm/month. Average fog deposition is 0.6 mm/month, which contributes to 3.4% of the water balance.

Figure 5-4 shows the spatial variability in the baseline water balance, water stress (% of demand unavailable), AET and fog deposition. The range of values of water balance with in the basin is large, ranging from -122.2mm/month to 207.7mm/month. The positive values are concentrated in the mountainous areas in the north and west of the Tana Basin. Negative average annual water balances occur across much of the floodplain and down to the coast. There are a number of reasons why a negative mean water balance may occur. Firstly, a particularly low water balance in some months may disguise a particularly high balance in others. A similar situation could be seen spatially, where some areas of the basin have a positive water balance, which supports negative water balances in other areas. If AET is greater than precipitation, WaterWorld assumes that the water is from groundwater flowing from upstream or stored in the cell (e.g. in the soil) (Mulligan, 2013b). Fog deposition only occurs in the Upper Tana.

As water stress takes into account the demand for water, it does not show the same spatial patterns as water balance, precipitation or AET. Water stress is lowest in the upland areas in the north of the basin and along the river network. There are also smaller areas with low average annual water stress values in the floodplain, in the south of the basin. The highest AET values occur in the semi-arid floodplains.

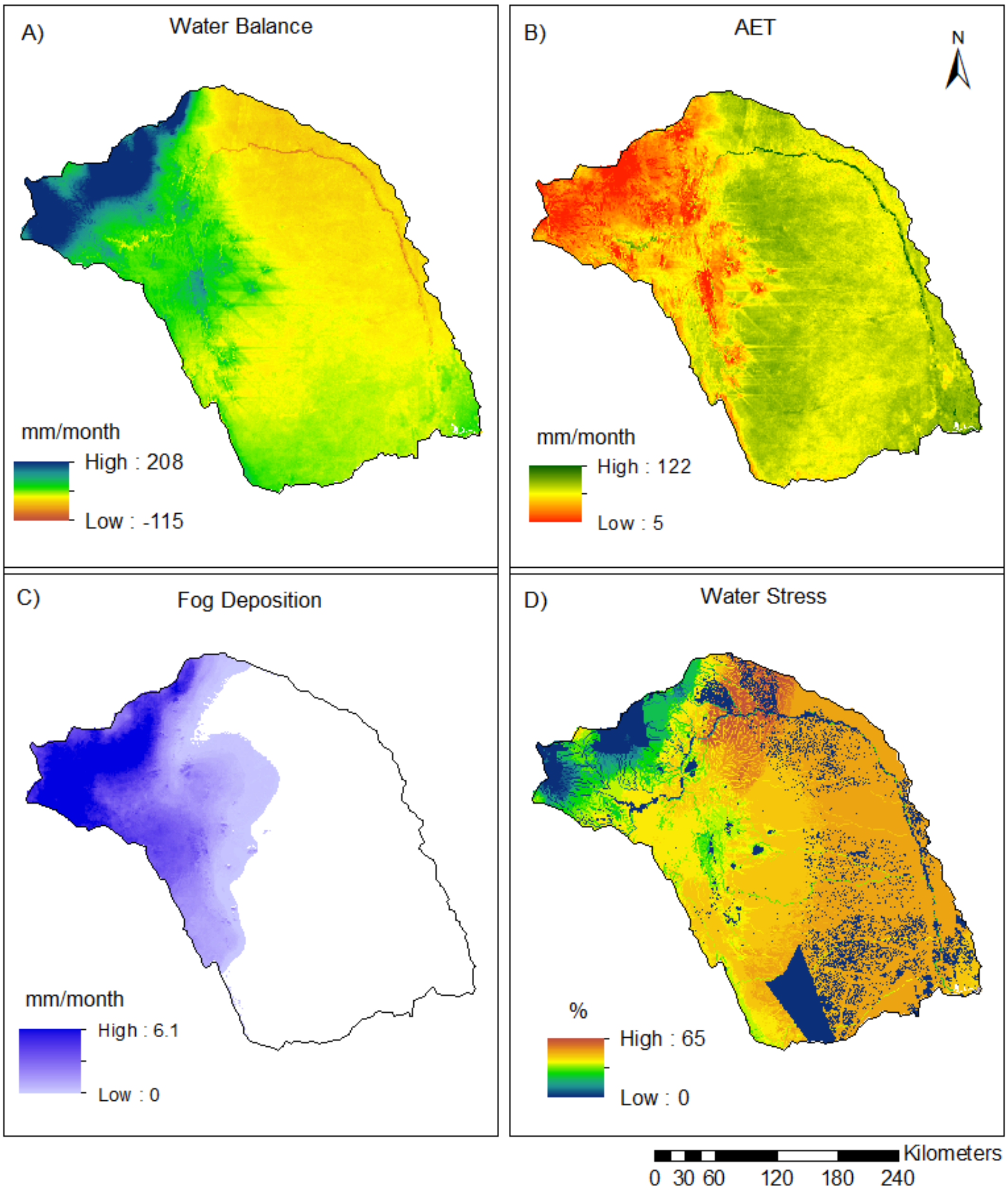

Figure 5-4: Spatial variation across the basin for baseline values of (A) water balance, (B) AET, (C) fog deposition and (D) water stress.

5.3.2 Baseline Annual Conditions by Administrative Area

By averaging annual water balance within district (or administrative area, introduced in Figure 1-4), it is possible to see a clear spatial difference in water stress and water balance across the basin. The district-average water balance ranges from -44 to 96 mm/month. Figure 5-5 shows high positive values of water balance are seen in the districts in the upper reaches of the river in the northwest of the basin, while negative values of water balance are seen across the floodplain region (Kitui and Tana River counties in particular). The floodplain region has higher temperatures and significantly lower annual rainfall. The opposite is true of water stress. The lowest values are seen in the upper Tana and the mid to lower basin experiences much higher average annual water stress. The district-average water stress varies from 15% to 45%.

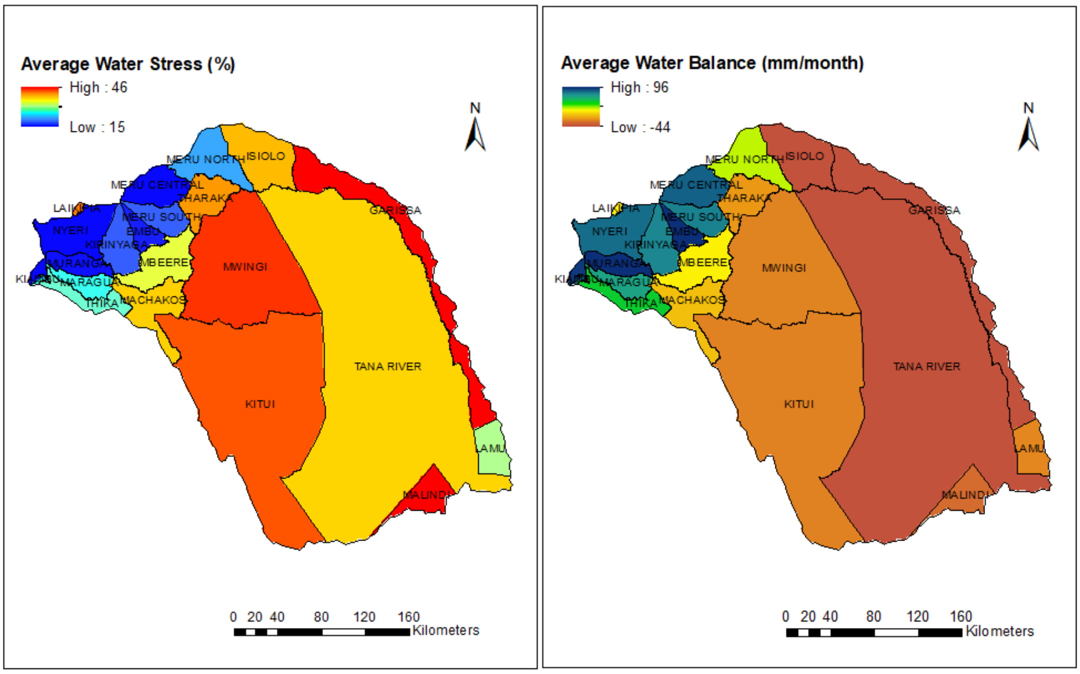

Figure 5-5: Water balance and water stress (% of demand unavailable or contaminated) averaged within each district. District boundaries data from World Resources Institute (2007).

Figure 5-6 further demonstrates the correlation between average annual water stress and average annual water balance.

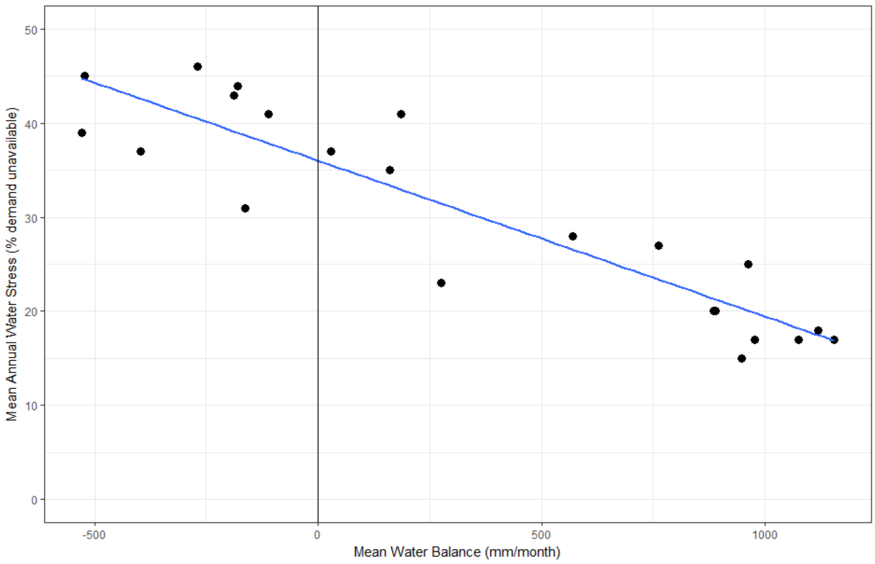

Figure 5-6: Correlation between water stress (% of demand unavailable or contaminated) and water balance. Each point is an administrative area.

5.3.3 Monthly Baseline Conditions

5.3.3.1 Water Balance and Water Stress

Figure 5-7 shows the monthly basin-average water balance and water stress. The wettest months – April, November and December – have positive water balance values, whereas all other months have negative mean water balances. The highest monthly water balance is 101 mm/month, which corresponds with the lowest water stress of 18%. The lowest water balances occur in August and September (-57.6 mm/month for both months). Basin-average monthly water stress varies from 18 to 43.5%.

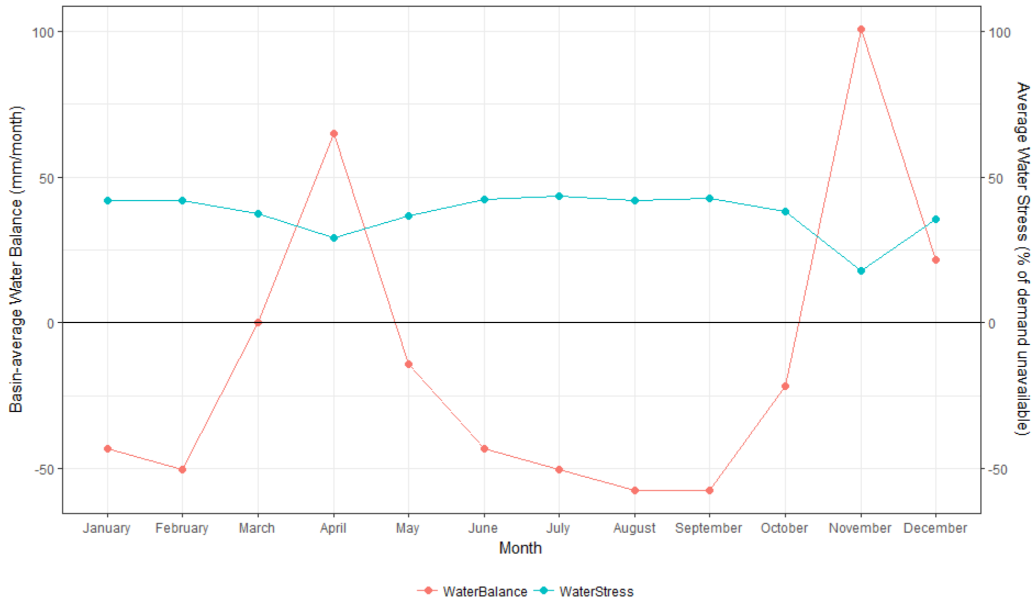

Figure 5-7: Baseline (average of 1950-2000) basin-average monthly water balance (red line) and average water stress (% of demand unavailable or contaminated) (blue line), from outputs from the WaterWorld (2016) model. Water balance is the sum of precipitation and fog inputs, minus AET.

5.3.3.2 AET

The baseline basin-average mean monthly AET does not vary greatly throughout the year; only ranging from around 65 to 79 mm/month. Figure 5-8 shows that there is some link to the change in average monthly temperature as the lowest AET values are seen in the cooler months, namely June and July. Between February and May, which are the hottest months on average, the mean AET remains at 72 mm/month.

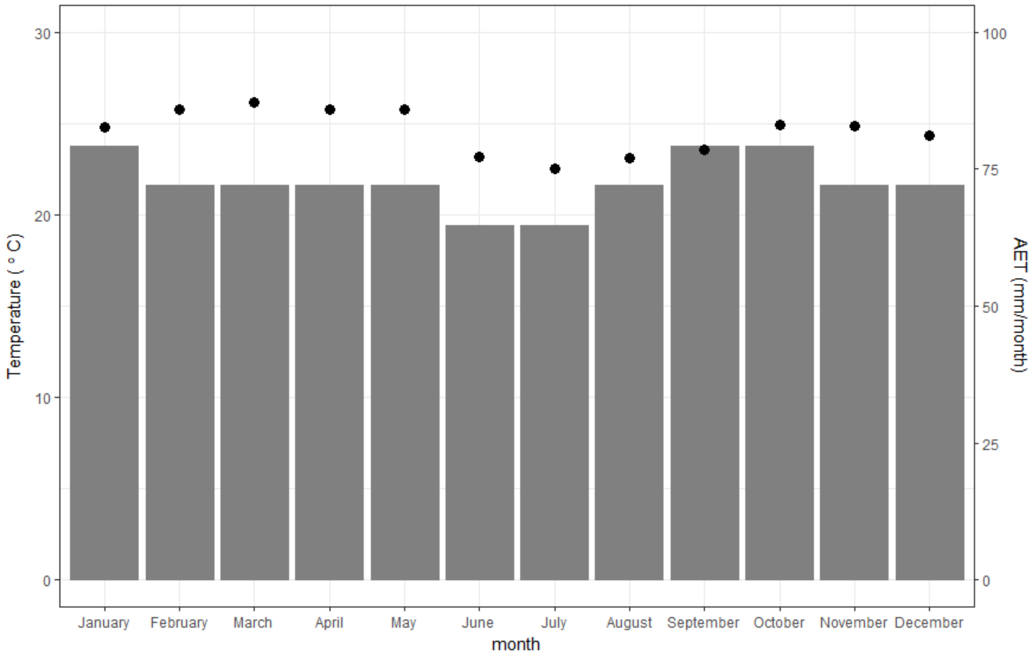

Figure 5-8: Baseline (average of 1950-2000) basin-average mean AET as calculated by the WaterWorld model and average monthly temperature.

5.4 Projected Future Changes

This section shows the changes in the main hydrological variables annually and monthly. First, the multi-model mean scenarios are considered and then the variation in results from the individual GCMs are presented.

5.4.1 Ensemble Mean – Annual Changes

A total of 12 multi-GCM ensemble scenarios (mean, mean-SD and mean+SD for the four emissions scenarios, which were introduced in Chapter 3) have been considered for each time horizon; the 2050s and the 2070s. Mean-SD can be considered a cool, dry projection, whilst the mean+SD is warmer and wetter.

5.4.1.1 AET

Much of the basin is projected to experience increases in AET of between 1 and 3 mm/month for the four multi-model mean scenarios by the 2050s. The spatial pattern of change is similar for the four RCPs. Increases in AET are projected for the majority of the basin but some areas of the upper Tana could see reductions in average annual AET of up to 2 mm/month. The frequency distributions of change in AET projected by the 2050s (Figure 5-9) show a similar range for the four RCPs. The changes (future minus present) across the study area range from around -2 to +5 mm/month for all four RCPs.

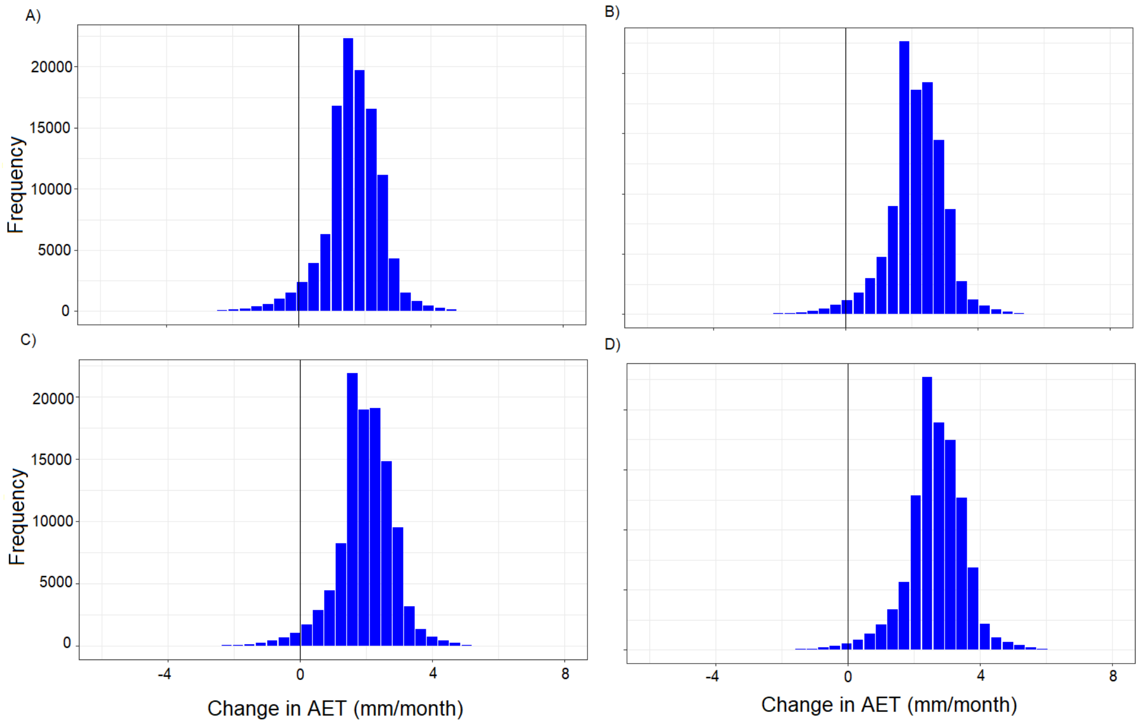

Figure 5-9: Frequency histograms for AET change for the Tana River Basin for the multi-model mean scenarios by the 2050s. A) RCP2.6, B) RCP4.5, C) RCP6.0 and D) RCP8.5.

5.4.1.2 Water Balance

The percentage changes (future – present) in Figure 5-10 shows that the differences in basin-average water balance between the baseline and the two future time horizons are substantial for most scenarios. Mean-SD scenarios all show decreases in mean annual water balance of 86-89% for the 2050s (2041-2060) and of 68-100% for the 2070s (2061-2080). As the basin-average baseline water balance is negative, these scenarios result in more negative values. By contrast, the multi-model mean and mean+SD, show increases in water balance. The multi-model mean scenarios lead to increases of 31-58% for the 2050s and 50-83% for the 2070s. The mean+SD scenarios lead to even greater increases, of up to 204% for the 2050s and 266% for the 2070s.

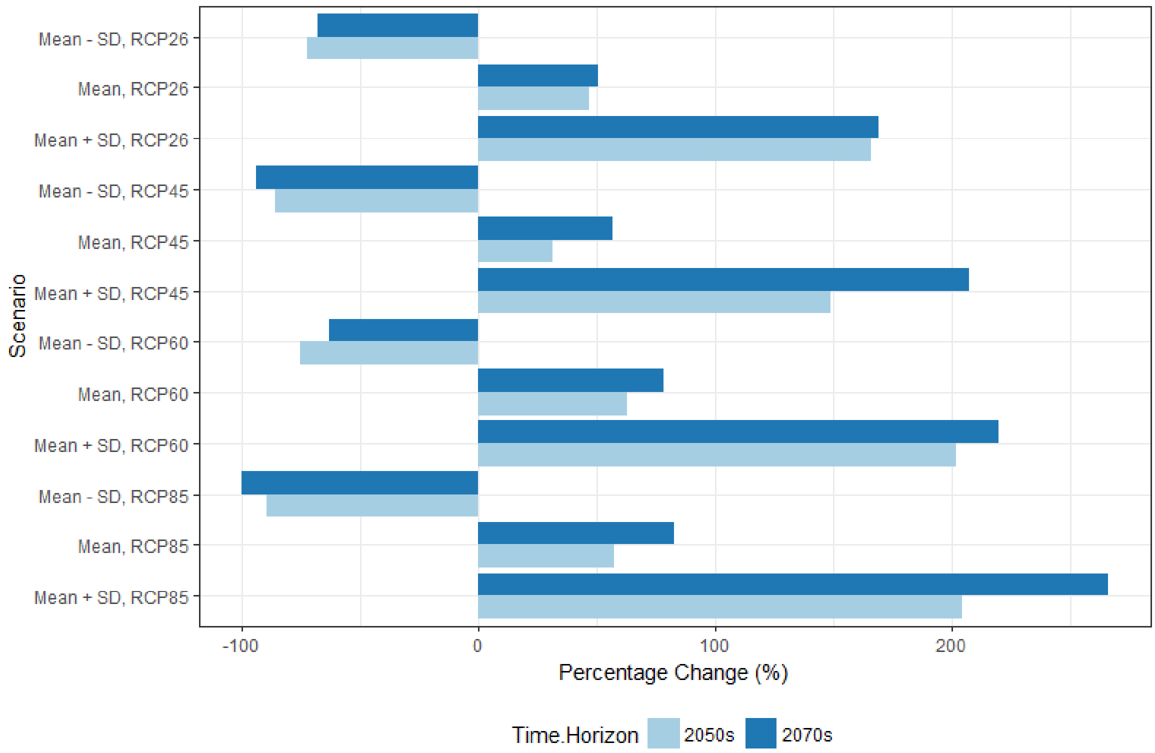

Figure 5-10: Percentage change in basin-average mean annual water balance projected by the multi-model climate change scenarios by the 2050s.

As well as the basin-average values, it is important to consider the variation in change across the river basin. The spatial pattern of change in annual water balance for the multi-model mean for the four RCPs for the 2050s is very similar. However, the changes become more pronounced in the upper Tana (northwest of the basin) with higher radiative forcing scenarios. The spatial changes in rainfall showed greater changes in the Upper Tana (Chapter 4). There is no sizeable differences between the change in fog deposition between the four RCPs so this does not contribute to the differences in water balance. The frequency distributions (Figure 5-11) show a similar range for the four RCPs. They show that the majority of the basin is projected to experience increases in water balance by the multi-model scenarios for the 2050s.

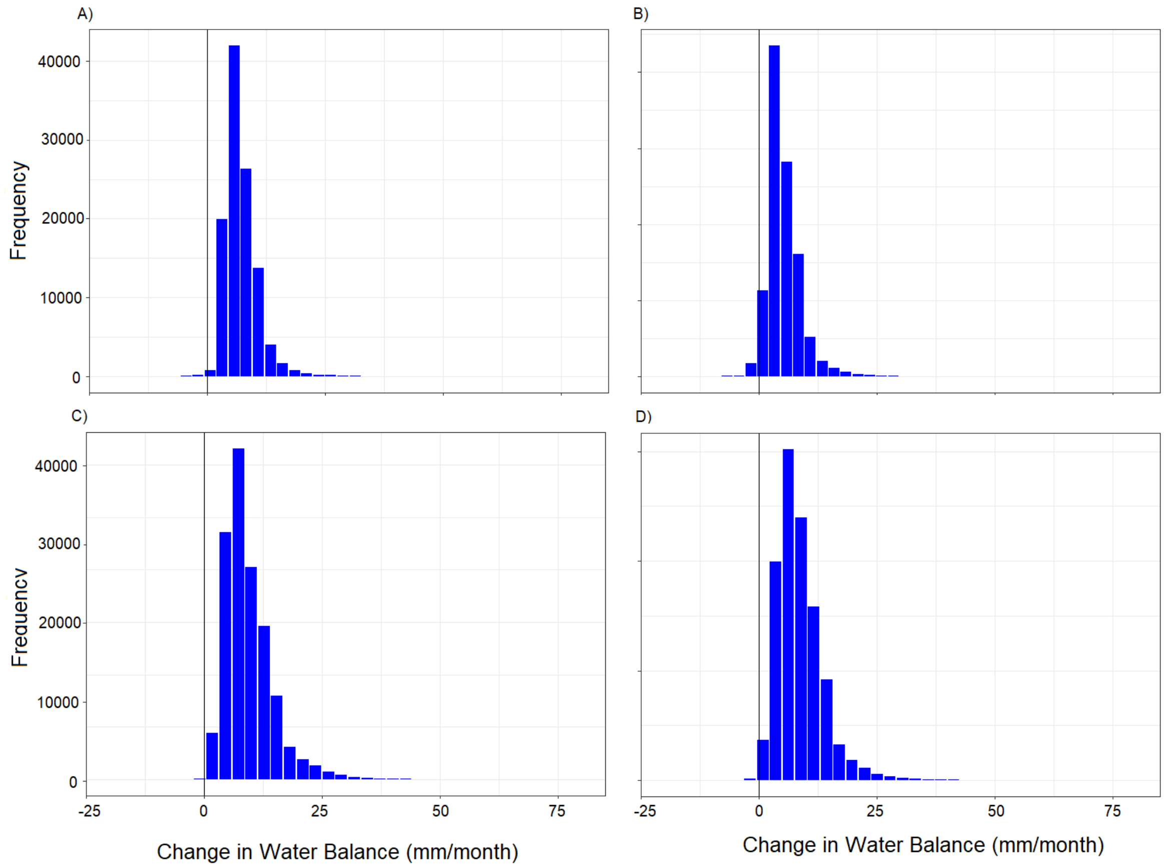

Figure 5-11: Frequency histograms for water balance change for the Tana River Basin for the multi-model mean scenarios by the 2050s. A) RCP2.6, B) RCP4.5, C) RCP6.0 and D) RCP8.5

By examining the changes in water balance averaged over administrative areas, it is possible to pick out changes that may be relevant to decision-makers. Figure 5-12 shows the changes by the 2050s and Figure 5-13 shows the changes by the 2070s, both using the four multi-model mean scenarios. Kiambu district, in the north west of the basin, experiences the greatest change in annual water balance under the four multi-model mean scenarios. By contrast, other areas, like Lamu, see smaller changes. Interestingly, Lamu is projected to see a decrease in average annual water balance under both RCP4.5 and RCP8.5 conditions. All other administrative areas see increases in average water balance. However, for some districts in the mid and lower basin, the absolute water balance values are projected to still be negative (i.e. AET is greater than rainfall and for interception under current conditions and in the future). An example of this is Tana River County, where the baseline water balance is -44 mm/month (shown on Figure 5-5) and the projected change by the 2050s is around +5 mm/month (Figure 5-12), so the absolute future water balance will remain negative.

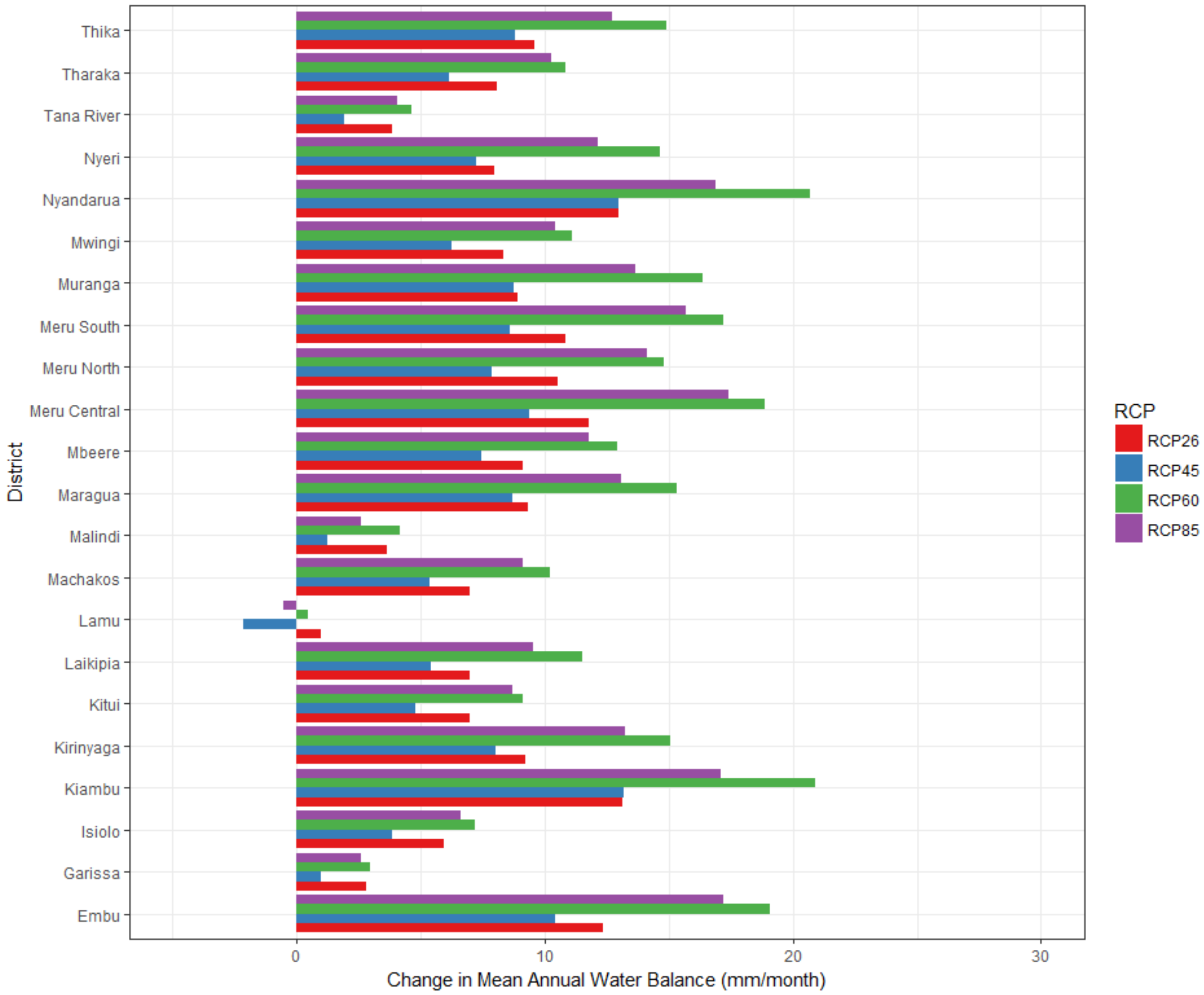

Figure 5-12: Change in annual water balance averaged within district boundaries for the 2050s. District boundaries data from World Resources Institute (2007).

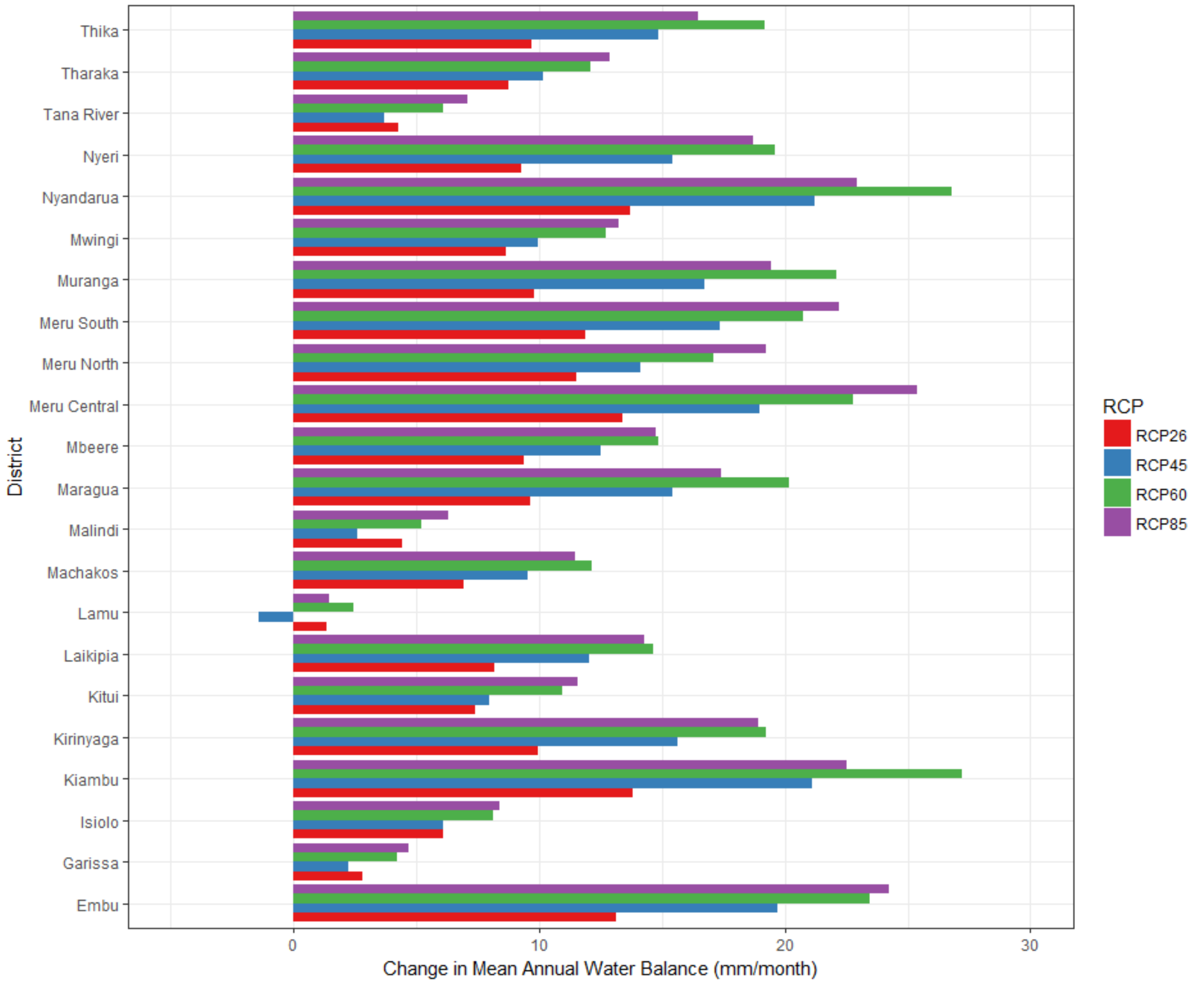

Figure 5-13: Change in annual water balance averaged within district boundaries for the 2070s. District boundaries data from World Resources Institute (2007).

5.4.1.3 Combined (Changes in Fluxes)

Table 5-5 shows the annual contributions of the different fluxes to projected change in water balance from the multi-model climate change scenarios. The mean and mean+SD scenarios result in increases in water balance. This change is dominated by changes in rainfall. Temperature-driven increases in evapotranspiration are seen in all scenarios, but the changes are minor compared to changes in rainfall. Changes in annual fog inputs are minimal and do not account for a significant contribution to water balance. Baseline fog inputs were also minimal for the majority of the basin.

Table 5-5: Annual basin-average mean change in different fluxes included in the water balance equation for the 2 time horizons, the 2050s and 2070s, for the multi-model mean scenarios.

Time Horizon	Scenario	Change in Water Balance (mm/month)	Change in rainfall (mm/month)	Change in AET (mm/month)	Change in fog inputs (mm/month)
2050s	Mean, RCP2.6	6	7	2	0.03
	Mean+SD, RCP2.6	21	23	2	0.03
	Mean-SD,RCP2.6	-9	-8	1	0.03
	Mean, RCP4.5	4	6	2	0.03
	Mean+SD, RCP4.5	19	22	3	0.03
	Mean-SD, RCP4.5	-11	-10	1	0.03
	Mean, RCP6.0	8	10	2	0.03
	Mean+SD, RCP6.0	26	28	2	0.03
	Mean-SD, RCP6.0	-10	-8	1	0.03
	Mean, RCP8.5	7	10	3	0.03
	Mean+SD, RCP8.5	26	29	3	0.03
	Mean-SD, RCP8.5	-11	-10	2	0.02
2070s	Mean, RCP2.6	6	8	2	0.02
	Mean+SD,RCP2.6	21	23	2	0.03
	Mean-SD, RCP2.6	-9	-8	1	0.02
	Mean, RCP4.5	7	10	2	0.03
	Mean+SD, RCP4.5	26	29	3	0.03
	Mean-SD, RCP4.5	-12	-10	2	0.02
	Mean, RCP6.0	10	12	2	0.03
	Mean+SD, RCP6.0	28	31	3	0.03
	Mean-SD, RCP6.0	-8	-6	2	0.02
	Mean, RCP8.5	11	14	4	0.03
	Mean+SD, RCP8.5	34	38	5	0.03
	Mean-SD, RCP8.5	-13	-10	3	0.03

5.4.1.4 Average Annual Water Stress

Figure 4-14 shows the change in average annual water stress across the basin for the four multi-model mean scenarios. The changes in average annual water stress across the basin do not show the same pattern as changes in water balance or precipitation. For RCP2.6, some areas see an increase in water stress of up to a maximum of 12.5%, whereas others see a decrease of up to -16.66%. The differences between the four multi-model mean scenarios are not marked. For RCP8.5, there are more negative values in the west of the basin.

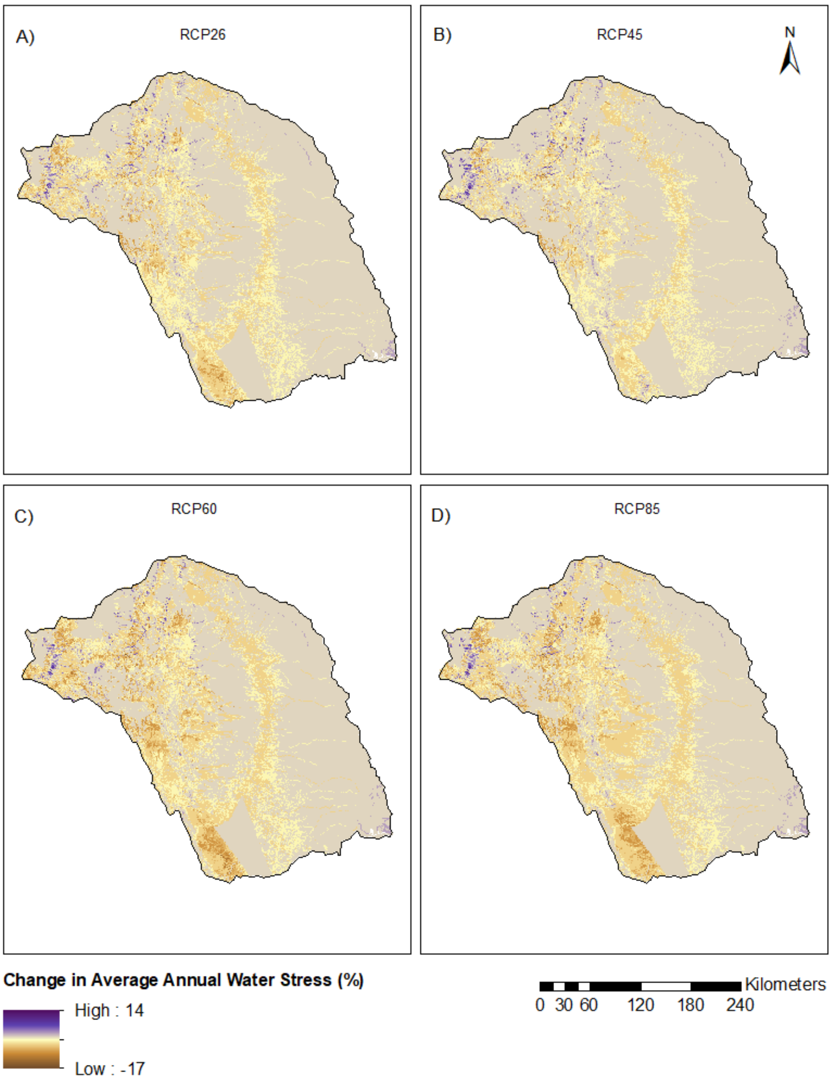

Figure 5-14: Change in average annual water stress (% of demand unavailable or contaminated) across the Tana River Basin for the four multi-model mean scenarios for the 2050s: A) RCP2.6, B) RCP4.5, C) RCP6.0 and D) RCP8.5.

Figures 5-15 and 5-16 shows the changes in water stress averaged over the administrative areas within the basin for the two time horizons. Under RCP2.6 for the 2050s period, all administrative areas see a decrease in water stress. However, Lamu shows an increase in water stress under RCP8.5 conditions for the same time period. Increases in water stress are also shown in the 2070s for both RCPs. The variation between the different RCPs for Lamu is similar to that seen in water balance (Figures 4-12 and 4-13).

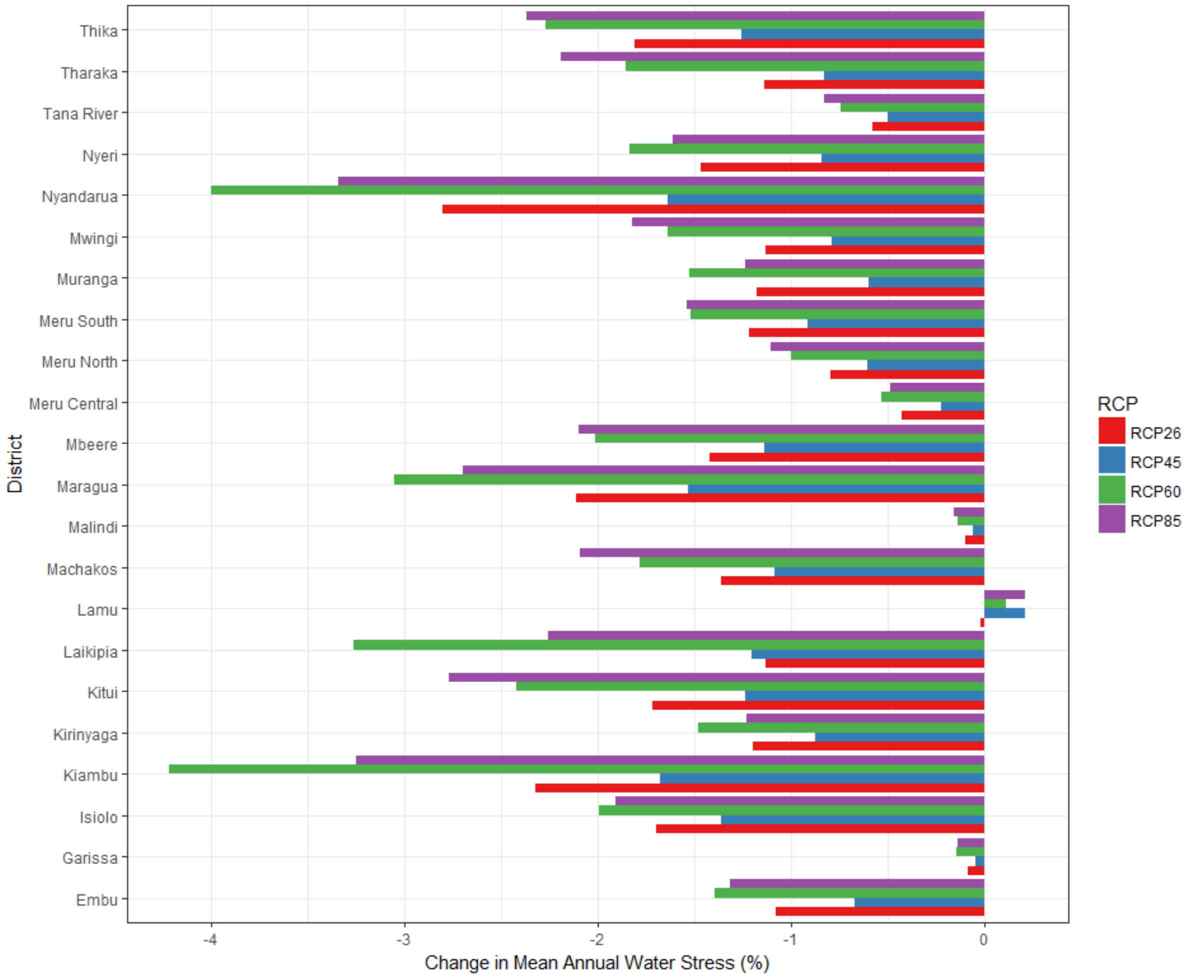

Figure 5-15: Change in water stress (% of the demand unavailable or contaminated) for the 2050s averaged within districts fully or partially contained within the Tana River Basin. District boundaries data from World Resources Institute (2007).

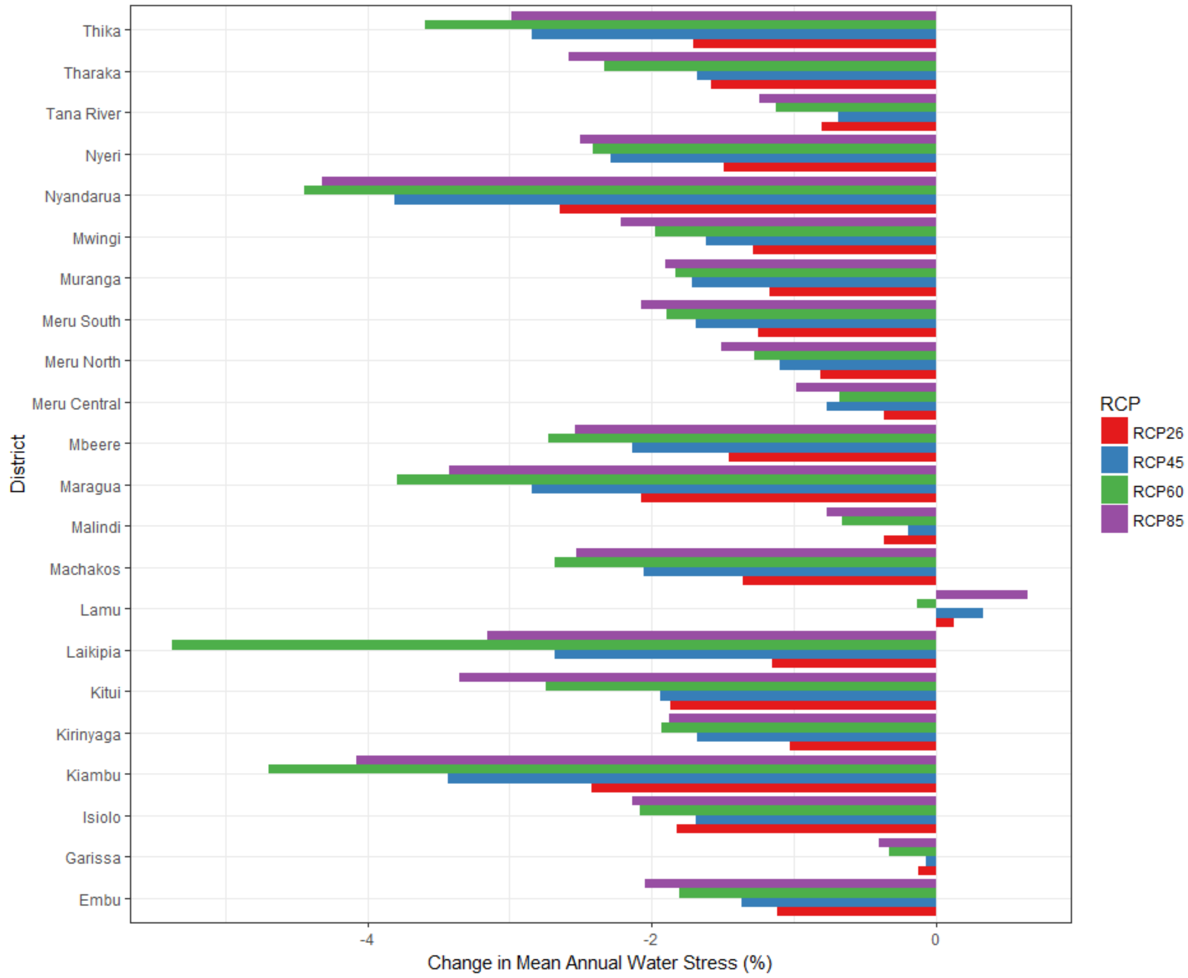

Figure 5-16: Change in water stress (% of the demand unavailable or contaminated) for the 2070s averaged within districts fully or partially contained within the Tana River Basin. District boundaries data from World Resources Institute (2007).

5.4.2 Monthly Changes Projected by the Ensemble Mean

5.4.2.1 Water Balance

Figure 5-17 shows the monthly percentage change for the multi-model climate change scenarios. The four multi-model mean scenarios show increases in water balance in the wettest months but decreases in mean water balance in the dry season between May and September. The differences between the four RCPs for the multi-model mean are minimal, but there is greater variation in the rainy seasons. The pattern of change is similar for both time horizons and the difference between the 2050s and 2070s is smaller compared to the difference from the baseline to the 2050s.

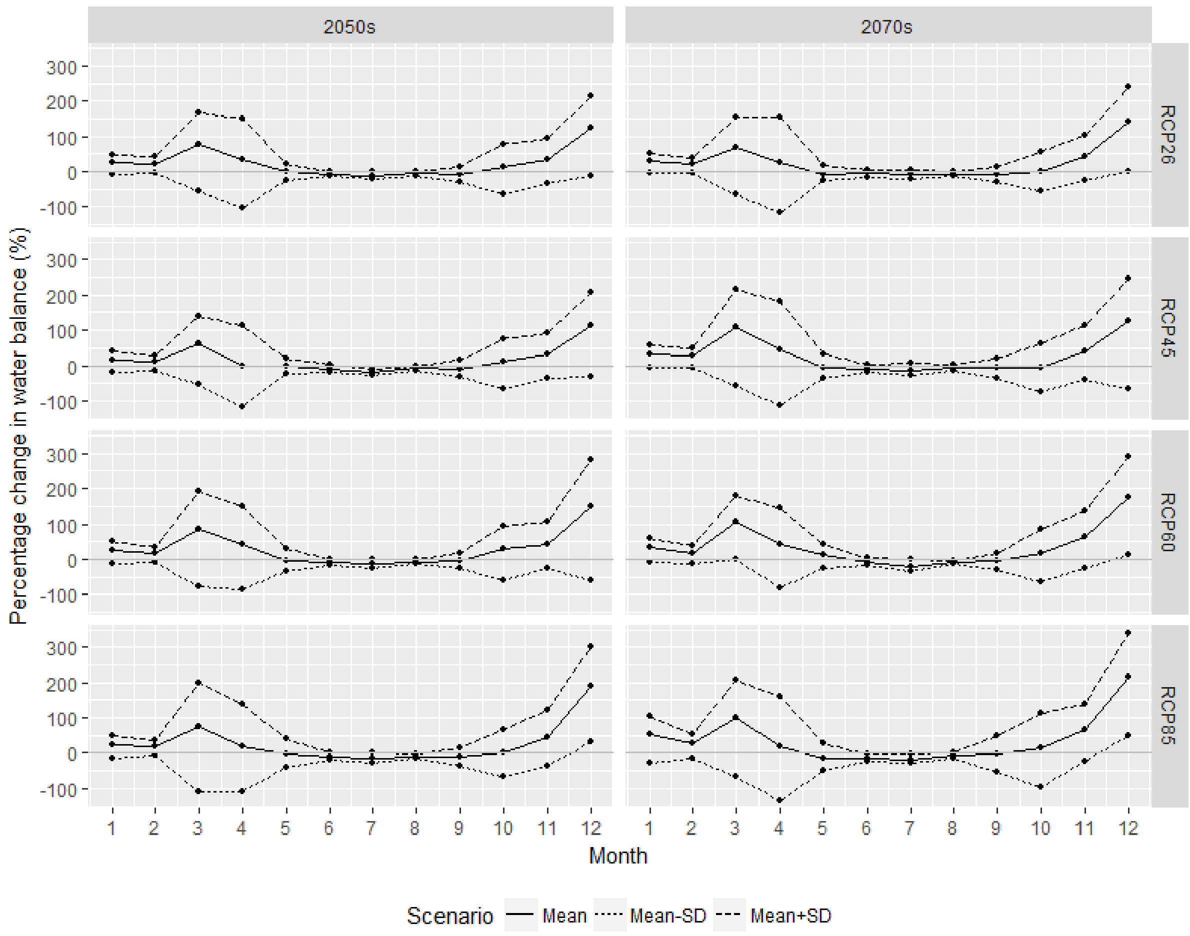

Figure 5-17: Percentage change in basin-average monthly water balance for the multi-model scenarios (mean and mean+/- SD across the multi-GCM ensemble) from the baseline to the 2 time horizons, 2050s and 2070s, and the four RCPs.

5.4.2.2 Water Stress

Figure 5-18 shows the monthly changes to basin-average mean monthly water stress for the multi-model scenarios for the 2050s. The greatest changes occur in March, November and December, during the wettest months. Reductions in water stress are projected for all of these months (i.e. more of the water demand is available compared to the baseline). The greatest difference between the four RCPs is seen in December. The multi-model mean scenario for RCP8.5 projects around a 10% reduction in basin-average water stress in December.

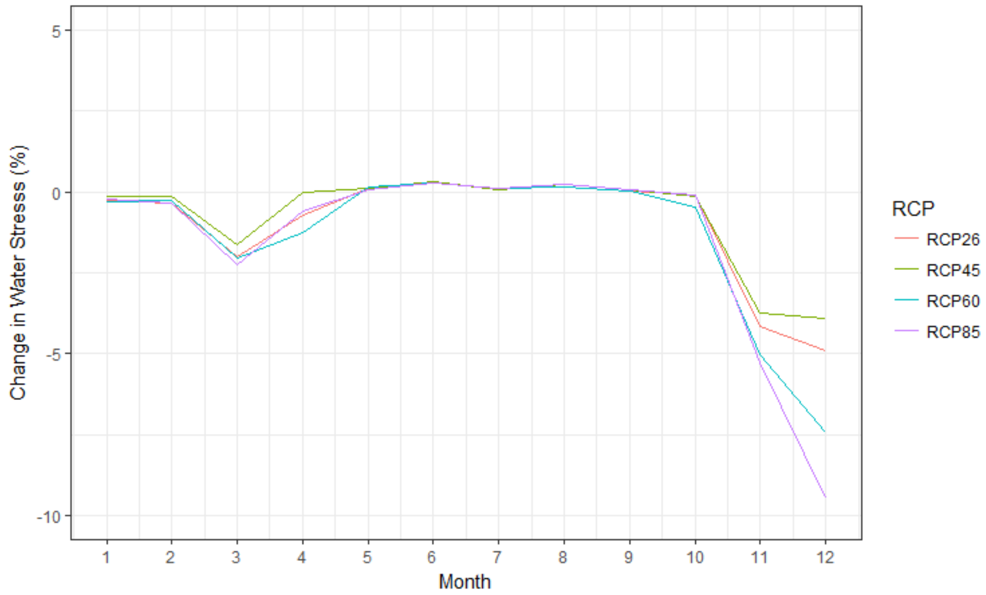

Figure 5-18: Change in basin-average water stress (% of demand unavailable or contaminated) for the four multi-model scenarios by the 2050s.

5.4.2.3 Runoff at Garissa

Runoff changes at Garissa have been examined using the multi-model mean scenarios. Monthly changes in mean runoff (accumulated water balance) at the Garissa gauging station were found using WaterWorld's 'Define Points of Interest' tool, using the coordinates of the gauging station. It was not possible to get other statistics for the POI at Garissa so the standard deviation cannot be presented.

Average monthly flows at Garissa are projected to increase by 29-48% in the wettest month and decrease by 16-23% in the dry seasons by the 2050s using the multi-model mean scenario. This is shown in Figure 5-19. Annually, this is an average increase of between 8 and 21% using the multi-model mean. For the 2070s, the percentage changes from the baseline vary from 12 to 25% increases for the same scenarios. The mean-SD scenarios project decreases in runoff at Garissa in the majority of months. Annually, this is an average decrease of 21-26% from the baseline by the 2050s and 20-25% decrease from the baseline for the 2070s. By contrast, the mean+SD scenarios lead to higher runoff at Garissa for all months for most RCPs and time periods. Two exceptions to this are June for RCP2.6 and July for RCP4.5, both for the 2050s. The multi-model mean+SD scenario leads to minor reductions in runoff at Garissa in these two cases. Annually, this is an average percentage increase of 44-60% for the 2050s and 47-86% for the 2070s.

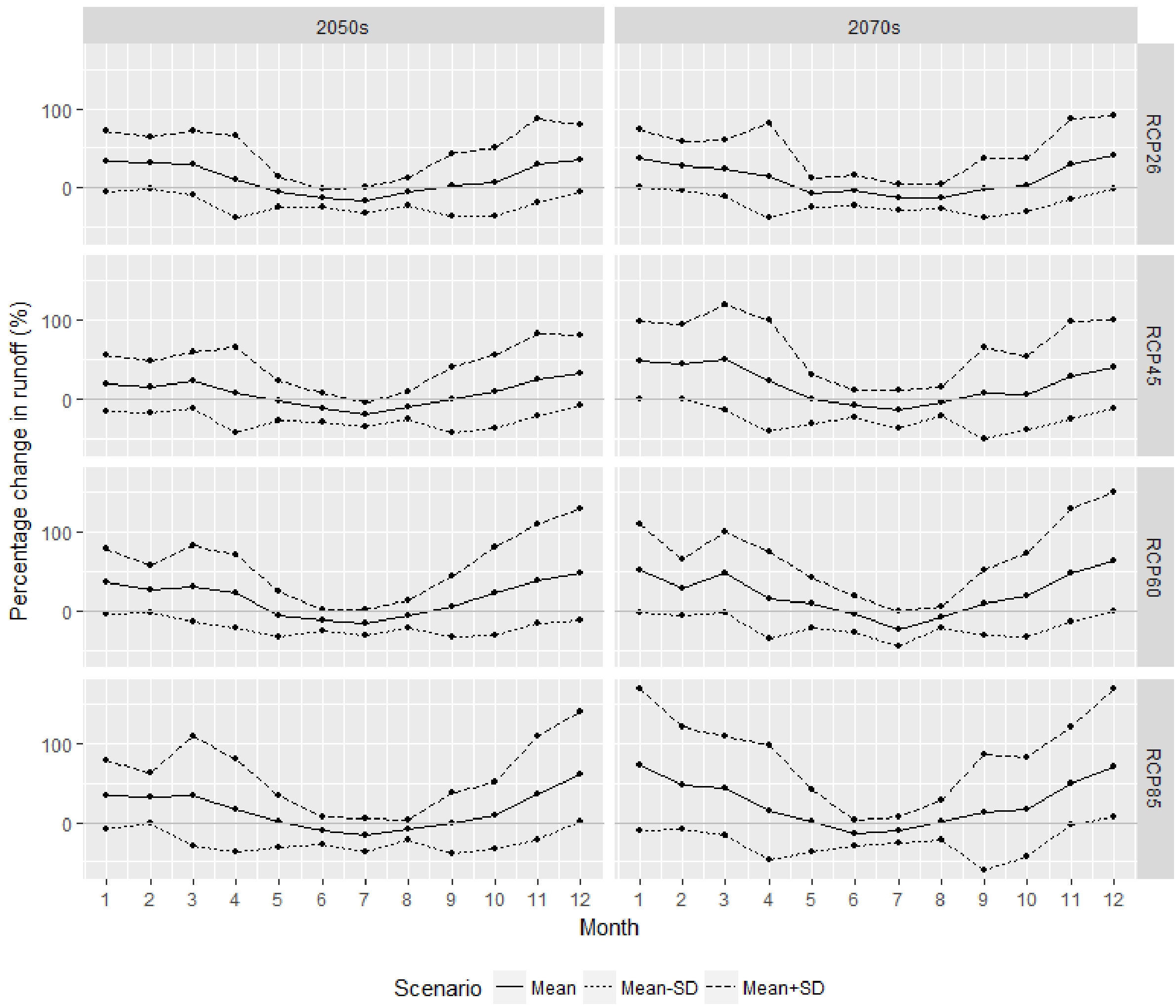

Figure 5-19: Percentage change in runoff (calculated in the model as water balance cumulated downstream) from the baseline at Garissa for the multi-model scenarios for the 4 RCPs and 2 time horizons.

<u>5.4.3 Spread of Projections by Individual GCMs</u>

In addition to examining the multi-model means, it is important to look at the projections of the individual GCMs and the differences between them.

5.4.3.1 AET

Figure 5-20 shows the range of projections over the different GCMs for annual changes to basin-average mean AET for the four RCPs and two time horizons. For the 2050s, median changes in AET range from around 1.3 to 2.6 mm/month. For the 2070s (Figure 5-21), the difference between the median values for the different RCPs is greater; ranging from around 1.5 to 3.8 mm/month.

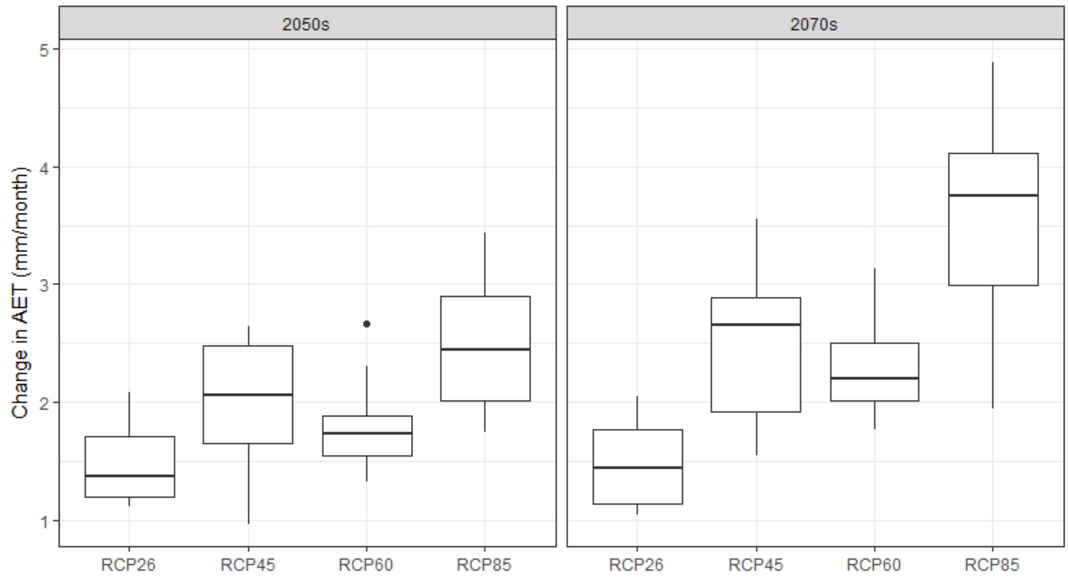

Figure 5-20: Change in basin-average mean monthly AET for the four RCPs for the two time horizons. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range. RCP2.6 (n=15), RCP45 (n=19), RCP60 (n=12) and RCP8.5 (n=17)

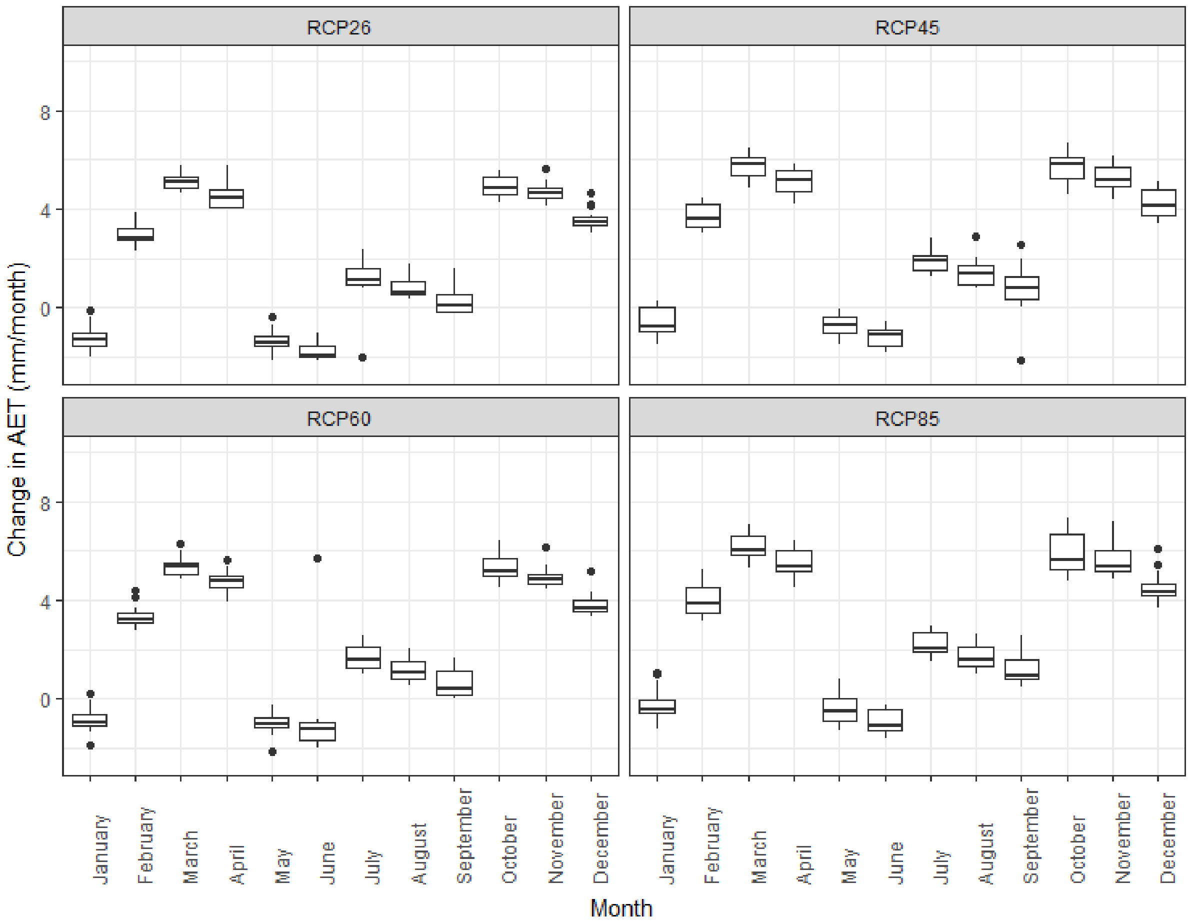

Figure 5-21: Change in basin-average monthly AET for the four RCPs by the 2050s. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range. RCP2.6 (n=15), RCP45 (n=19), RCP60 (n=12) and RCP8.5 (n=17)

5.4.3.2 Water Balance

As previously seen with precipitation (in Chapter 4, Section 5.2), there is a large variation in projected water balance changes between the individual models, as shown in Figure 5-22. The majority of models project increases in basin-average mean water balance. By the 2070s, there is an increase in the median values with increasing radiative forcing. These results correspond well with changes in rainfall, showing that this is the main influence on water balance in the region.

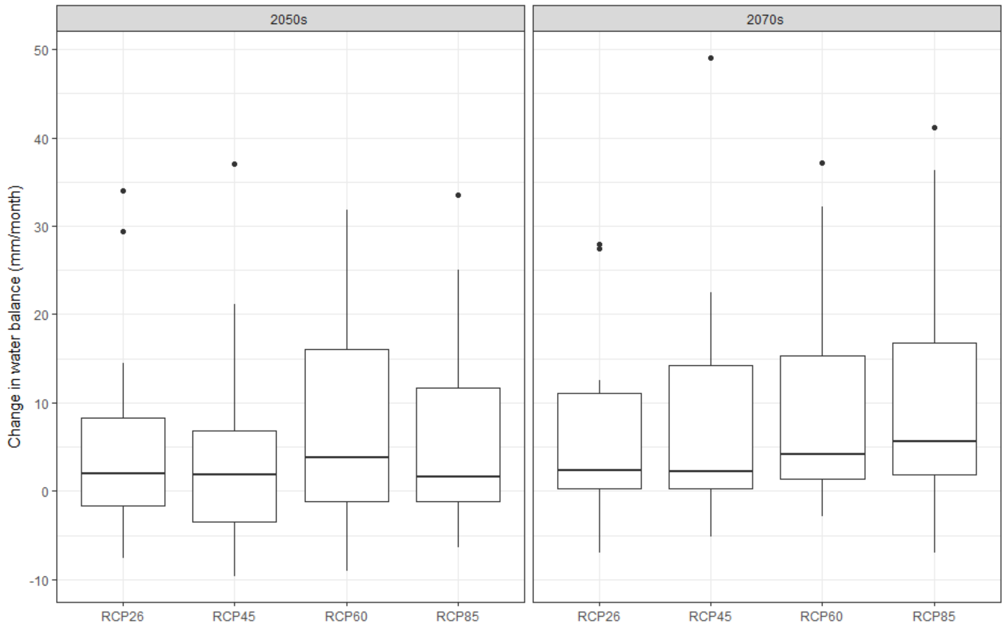

Figure 5-22: Box plots showing the range of basin-mean average annual water balance changes by RCP for 2050s and 2070s. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range. RCP2.6 (n=15), RCP45 (n=19), RCP60 (n=12) and RCP8.5 (n=17)

Figure 5-23 shows the water balance averaged within districts. Some of the largest administrative areas, such as Tana River and Mwingi have the smallest variation between the GCMs. By contrast, some of the districts in the Upper Tana, such as Embu and Kiambu, show a large spread of projections for the different GCMs.

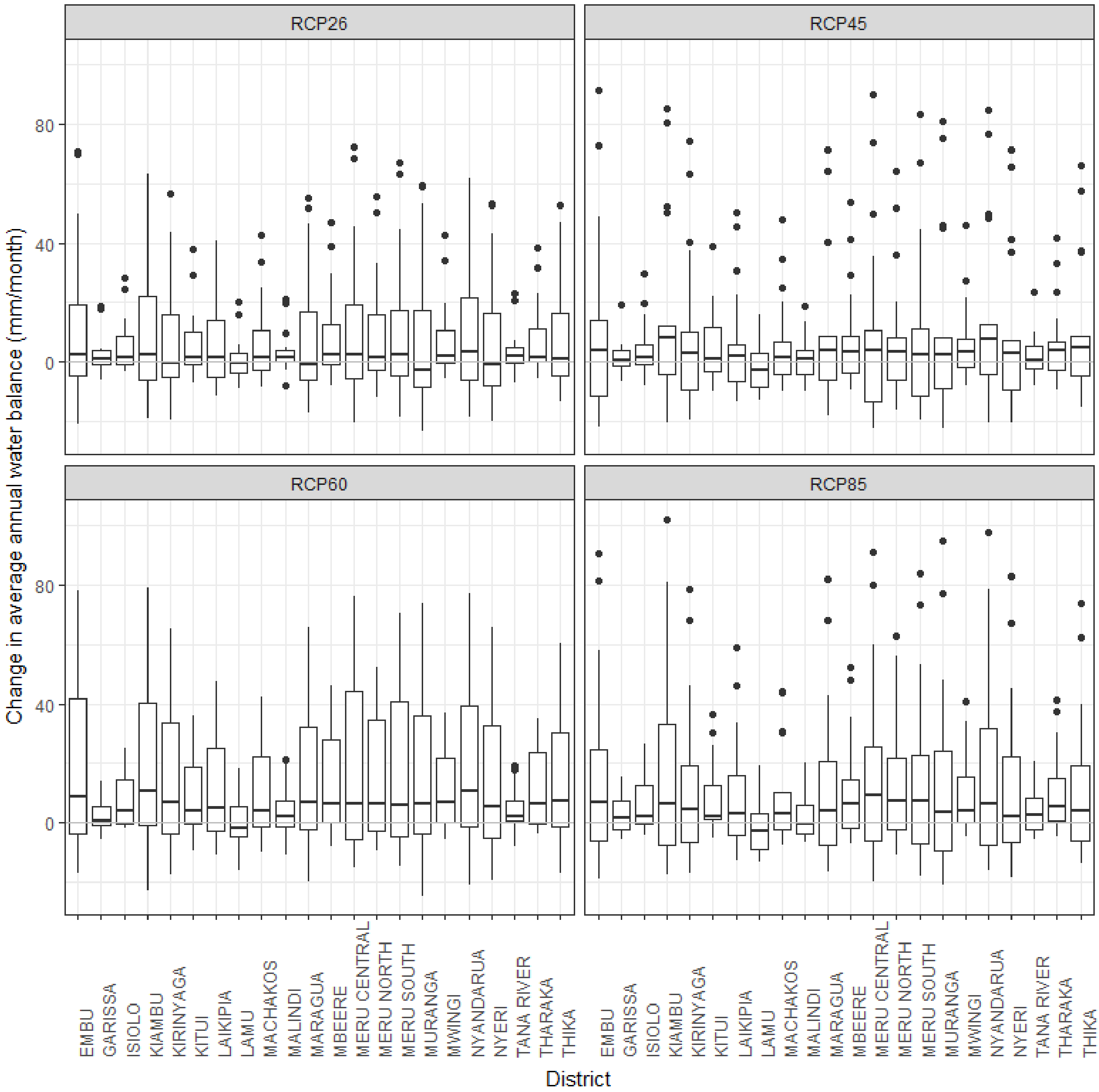

Figure 5-23: Variation between GCMs for water balance change by the 2050s, averaged within administrative area partially or fully contained within the Tana River Basin. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range. RCP2.6 (n=15), RCP45 (n=19), RCP60 (n=12) and RCP8.5 (n=17)

Monthly changes also show a large variation between the GCMs, as shown in Figure 5-24. As the changes between the GCMs is greater than the difference between the two time horizons only the 2050s have been plotted. The largest ranges of individual GCM projections occur in the rainy seasons, namely April and November. By contrast, there is relatively good agreement between the GCMs for changes in water balance in the dry seasons, particularly June-August. These months see decreases in water balance in the majority of cases. The changes in water balance correspond well to the spread of results shown for precipitation in Chapter 4 (Figure 4-12).

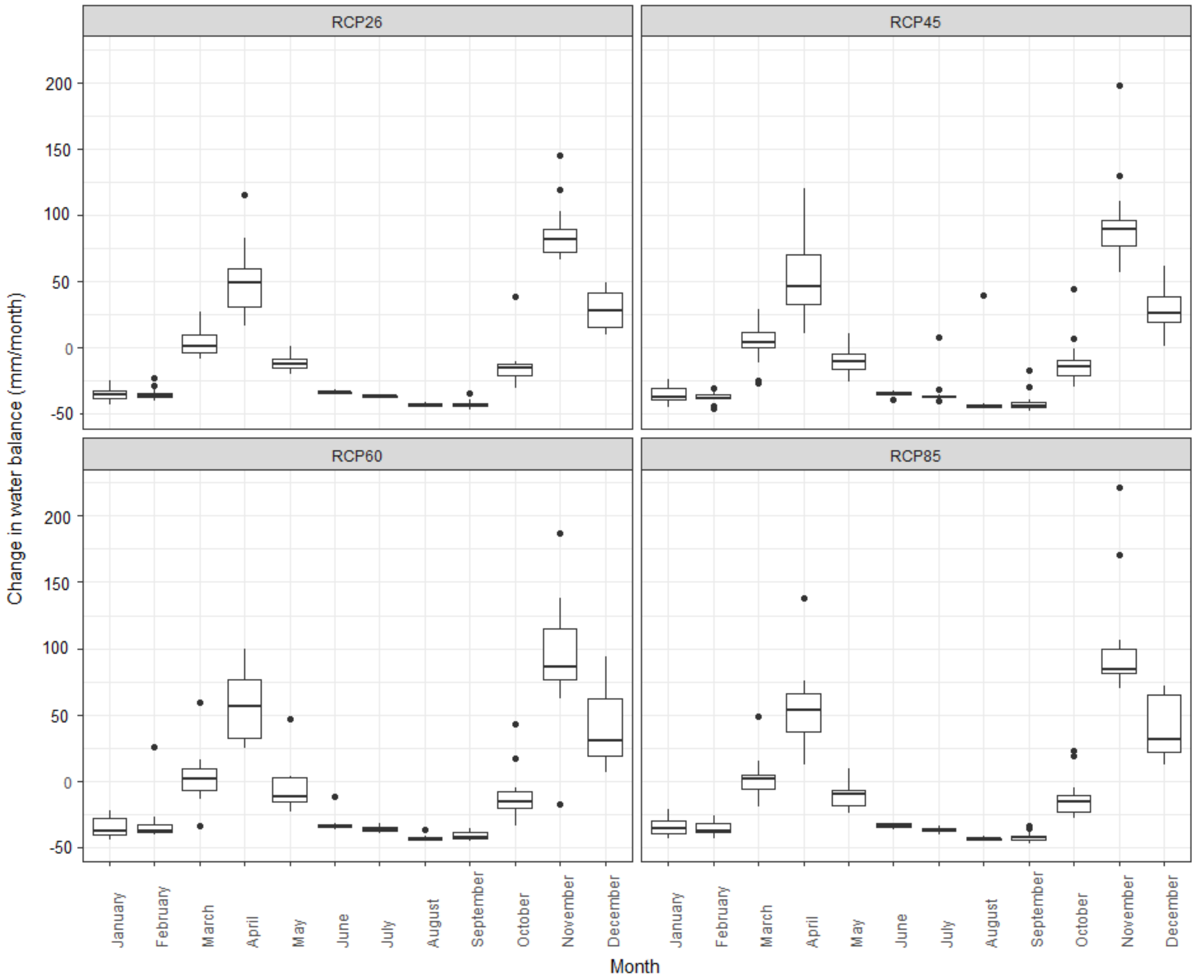

Figure 5-24: Seasonal distribution and variability of water balance (mm/month) for 2050s for the basin-average values. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range. RCP2.6 (n=15), RCP45 (n=19), RCP60 (n=12) and RCP8.5 (n=17)

5.4.3.3 Average Annual Water Stress

The change in average annual water stress is not as marked as the change in other hydrological variables. However, the majority of models project a decrease in average annual water stress, as shown in Figure 5-25. The percentage changes range from between 1% increases and 6% decreases in basin-average mean annual water stress.

The change in water stress averaged within districts is shown in Figure 5-26. Similarly to the water balance plots shown in Figure 5-22, some districts show a large spread between the individual model projections, whereas for other districts the models are more in agreement.

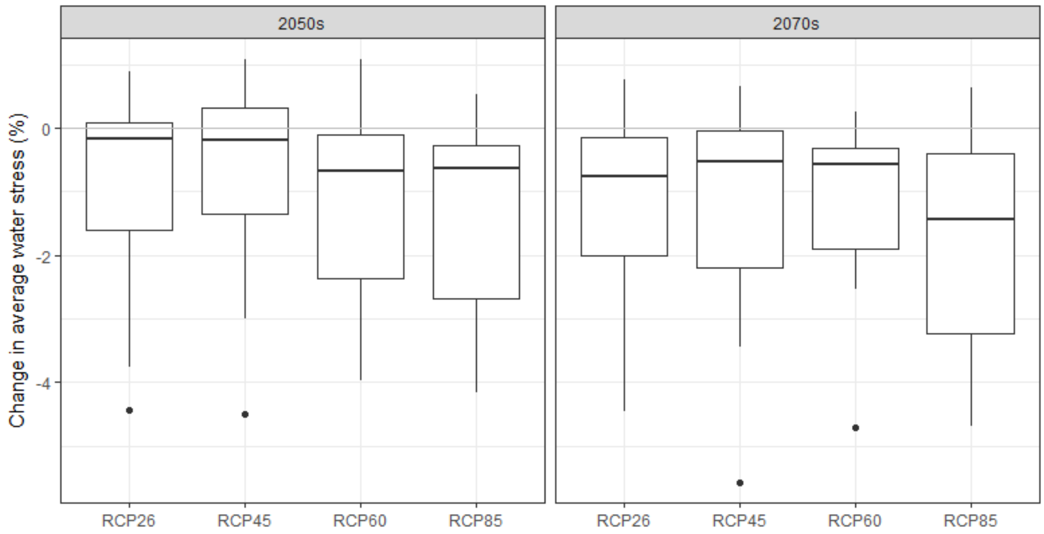

Figure 5-25: Change in basin-average mean annual water stress (% of demand unavailable or contaminated) for the two time horizons. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range. RCP2.6 (n=15), RCP45 (n=19), RCP60 (n=12) and RCP8.5 (n=17)

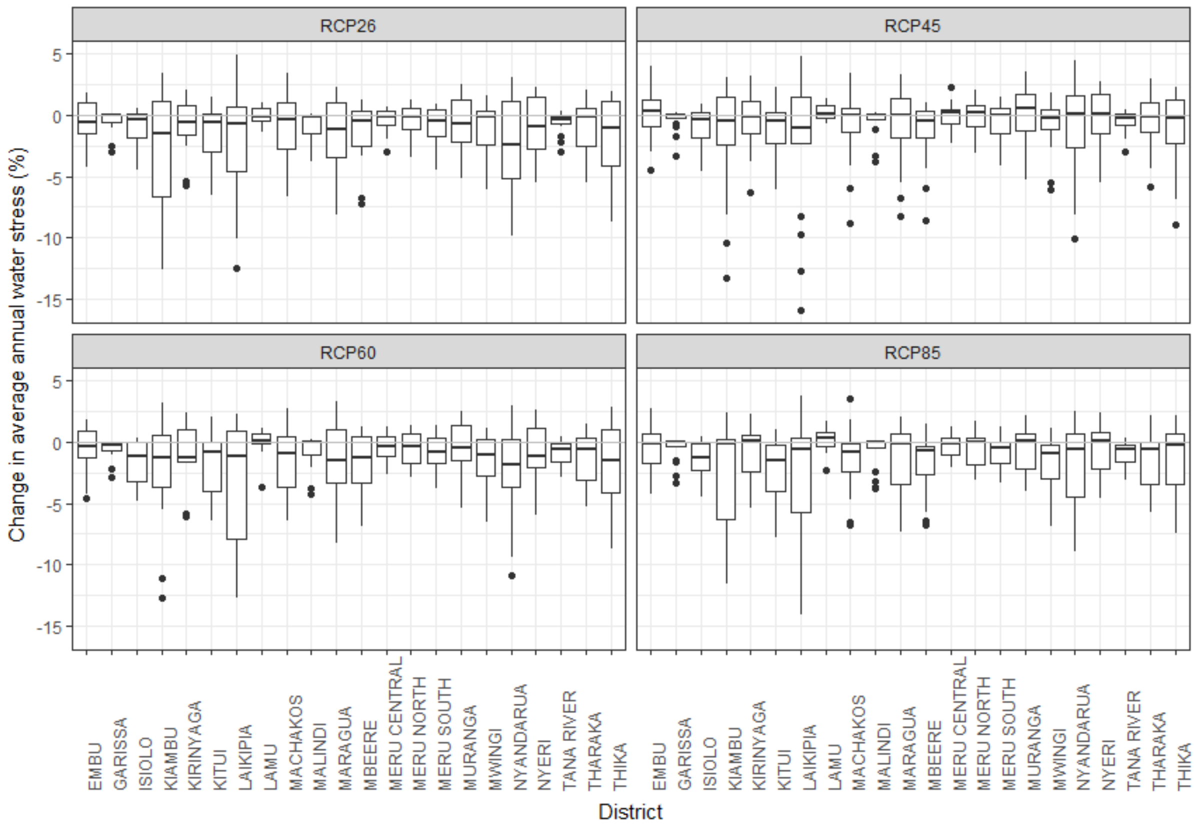

Figure 5-26: Change in average annual water stress by the 2050s within each district within the Tana River Basin. Outliers, shown as black circles, are extreme values, which are defined as outside 1.5 times the interquartile range. RCP2.6 (n=15), RCP45 (n=19), RCP60 (n=12) and RCP8.5 (n=17)

5.5 Discussion

5.5.1 Evapotranspiration

Under current conditions, AET does not vary much throughout the year. Projected changes to AET are relatively small compared to changes in the other variables examined here. In addition, the range of projected changes in AET between the individual GCMs are narrow, suggesting that the models agree more on changes to this variable. This suggests that temperature is the important influence here rather than precipitation. Areas with the highest temperatures, namely the low-lying floodplain and coastal region, have the highest evapotranspiration rates under current and projected future conditions. In East Africa, evaporation is predominantly affected by water availability rather than potential evaporative demand (Sircoulon *et al.*, 1999).

However, due to the various methods used, precise estimations of ET under different climate change scenarios is difficult (Kingston *et al.*, 2009). Previous studies have found a range of possible changes in AET in East Africa with climate change. Kirtman *et al.* (2013) projected changes of -5% to 5% across East Africa for an ensemble of 40 models under RCP4.5. By contrast, Faramarzi *et al.* (2013) projected up to 17% reductions in AET in the southern part of East Africa and up to 10% increase in the northern area.

5.5.2 Water Balance

The differences between the different RCPs for water balance are not sizeable, but a large variation in projections occurs between the different GCMs. Despite the wide range of projections, there is a general trend towards increased water balance, as a result of the increases in precipitation shown in Chapter 4, Section 5. The importance of rainfall changes was shown in Section 5.4.1.3, which presented changes to all fluxes in the water balance equation. This variation suggests that there could be a range of possible outcomes for water resources, even under the same RCP scenario and demonstrates the high uncertainties.

The spread of projections between the individual GCMs is greater for some districts than others. This does not appear to be linked to the size of the administrative region, as some of the largest districts have the smallest range of projections. Instead, this appears to be linked to the volume of current rainfall. The variation between the four RCPs is also highest in the Upper Tana, where rainfall is concentrated.

5.5.3 Water Stress

The majority of models project a decrease in average annual water stress, although the average percentage changes are minor compared to the other variables considered. The greatest change in water stress is projected for December. The greatest difference between the four RCPs is also seen in this month. Like water balance, average annual water stress is projected to remain highly spatially variable in the future. The demand part of the water stress calculation includes population and per capita domestic and industrial demand. These are likely to increase in the future as the volume of water available changes.

5.5.4 Runoff at Garissa

Some of the changes found in this research are similar to those found by Nakaegawa and Wachana (2012), who used a global hydrostatic AGCM and a 0.5°–mesh global river-routing model with the SRES emissions scenario A1B. Their results projected average annual flow at Garissa would increase in all months and that increases would be most significant between November and March. This result is different from those presented here, which show decreased flows in the dry seasons, particularly June, July and August. Sood *et al.* (2017) also modelled changes in mean annual flow at Garissa to increase by 90% by the end of the century for RCP4.5 and 200% for RCP8.5. These figures are significantly higher than the multi-model mean projections presented here, which ranged from 8-21% for the 2050s and 12-25% for the 2070s. Sood *et al.* (2017) only used six GCMs for their analysis, so their results may not portray the full range of projections and uncertainty. Here, between 12 and 19 GCMs were used, depending on the RCP.

Similar changes in runoff have been projected for other basins in East Africa. Githui *et al.* (2009) estimated changes in runoff in the Nzoia catchment in western Kenya by the 2050s. They found 6% to 115% increases in runoff, depending on the specific scenario used. Kim and Kaluarachchi (2009) examined the Upper Nile basin in Ethiopia and found a large range of possible changes (from 25% reductions to increases of 32%) in runoff by the 2050s.

5.5.5 Limitations of WaterWorld

The WaterWorld model has provided policy-relevant information but there are a number of limitations that should be considered alongside these results. WaterWorld calculates the average for the 20-year period, so it is not possible to see the variations between years (i.e. the climate variability). In addition, a different number of GCMs are available for each RCP in WaterWorld. There are 19 GCMs available for RCP4.5 but only 12 for RCP6.0. However, the results have shown that the spread of model results does not seem to be affected by this, i.e.

there is a similar range of results between the individual models present for all of the RCPs.

There are a number of methods for calculating ET, so there may be limitations with the method used in WaterWorld. The methods for calculating ET from remotely sensed data include deterministic methods (e.g. Olioso *et al.* (1999)), vegetation index methods (Allen *et al.*, 1998) and empirical methods (Seguin and Itier, 1983). ET is a key ecosystem variable (Ukkola and Prentice, 2013). WaterWorld calculates ET from globally available datasets. However, in a highly heterogeneous environment like the Tana River Basin, spatial modelling tools may more accurately and practically represent ET than field experiments (Pandeya and Mulligan, 2013). Mulligan (2015) notes that for Africa the relationship between long term mean annual temperature according to WorldClim and the MODIS-estimated AET assembled by Mulligan (2011) is significantly weaker than other areas of the world. Higher temperatures do not necessarily correspond with higher AET.

Furthermore, this analysis did not take into account groundwater stores. One assumption made in this model is that at these spatial and temporal scales, losses to canopy, soil and groundwater are much less significant than the outcome of the fluxes of rainfall and evapotranspiration. WaterWorld assumes groundwater stores to be in equilibrium in the long term. Data on sub-surface water storage are not currently available in the SimTerra database so cannot be used in the model (Mulligan, 2013b). The GoK (JICA, 2013) estimates that around 24% of the population of the Tana catchment area is supplied water from groundwater sources. Groundwater is the major source of water for 80% of the population in rural Africa (MacDonald *et al.*, 2009).

5.5.5.1 Comparison with Observed Discharge Data

Although the observed precipitation data from rain gauges in the upper, mid and lower Tana basin all correspond well to the baseline precipitation (Chapter 4, Section 4.1), when the baseline results from the Garissa gauging station were compared with observed discharge values, they do not agree as well.

Observed discharge data from the Garissa gauging station was obtained from the Global Monthly River Discharge Data Set (RivDIS; Vorosmarty *et al.* (1998)). The monthly mean, minimum and maximum monthly discharge at Garissa for 1934-1975 are presented in Figure 5-27. The highest average discharges are seen in

May, but the highest discharges are seen in November. By examining the annual totals for the period, it is likely that the peak in maximum discharge in November have been affected by one extremely wet year (1961), where the highest discharge ever recorded occurred. This peak discharge was 3, 568 m^3s^{-1} (Maingi and Marsh, 2002), which is approximately 97.4 mm/month.

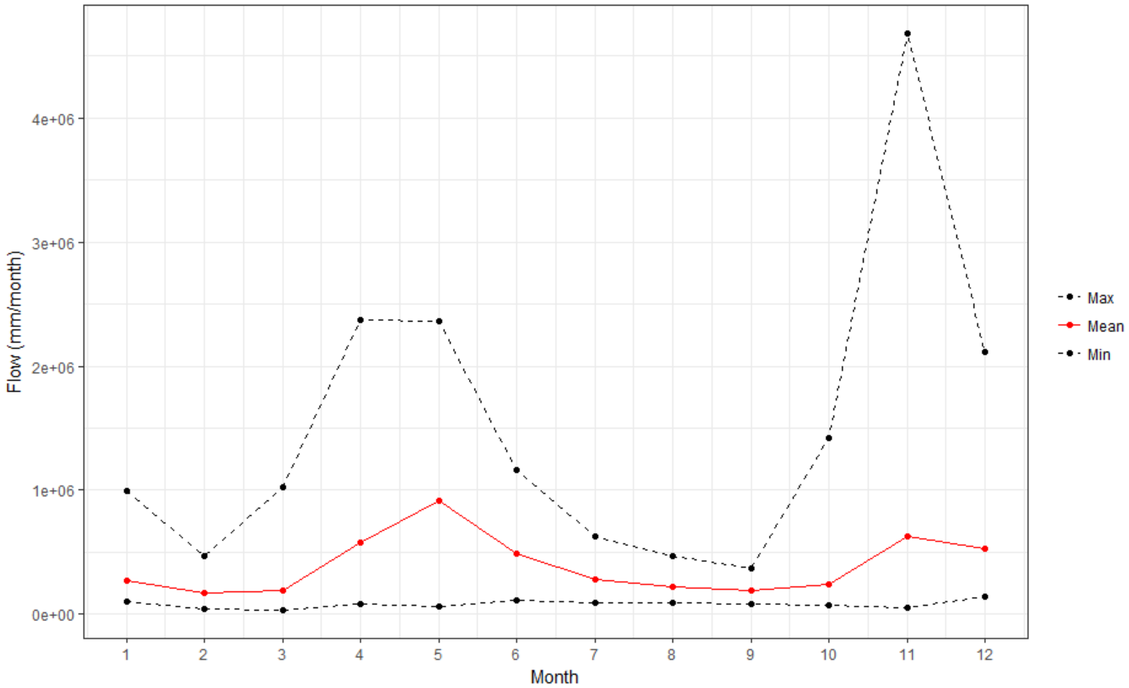

Figure 5-27: Observed max, min and average monthly discharge at the Garissa gauging station, 1934-1975. (Data from RivDIS, Vorosmarty et al., 1998).

The mean annual discharge in the observed data is $156m^3s^{-1}$ (also found by Duvail *et al.* (2012)). However, the baseline mean annual runoff (accumulated water balance) from WaterWorld for the coordinates of the Garissa gauging station is $290m^3s^{-1}$. This is nearly twice as much as the observed annual discharge.

Figure 5-28 shows the mean monthly runoff at Garissa from WaterWorld. The highest values are seen in March-May and November-December.

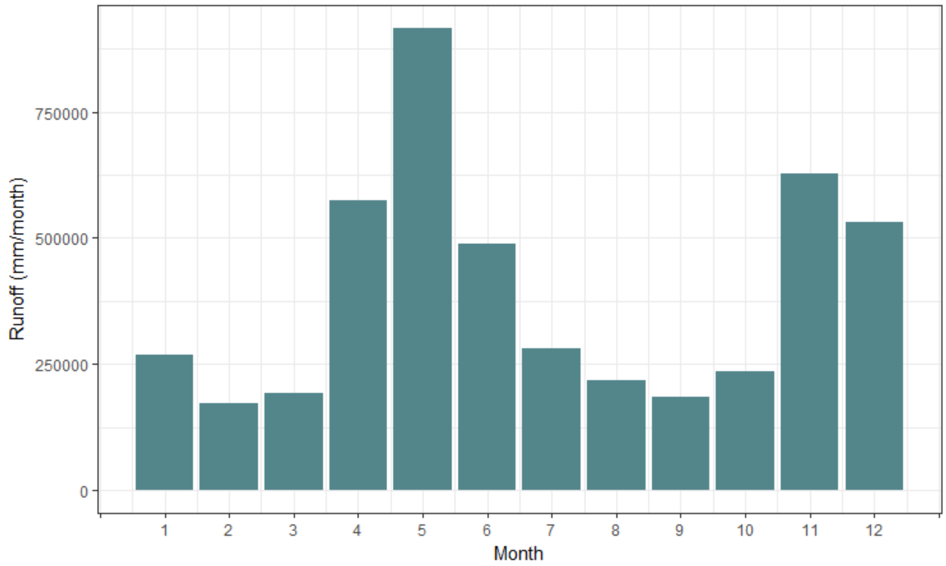

Figure 5-28: Baseline mean monthly runoff (accumulated water balance) at Garissa from the WaterWorld model.

The observed flow values were converted to mm/month to compare with the baseline results from WaterWorld. Figure 5-29 shows the level of agreement between the two sets of flow data. The coefficient of determination is 0.45, showing that there is not a good agreement between the two datasets. There is a greater agreement between the two datasets for the lower flows than the higher flows. The WaterWorld baseline overpredicts the average flow in the wettest months (April, May and November). Mulligan and Burke (2005) compared modelled accumulated water balances (runoff) against flows recorded in the GRDC database (GRDC, 2012) for 17 catchments in Costa Rica, covering humid to semi-arid environments. In some cases, including for catchments with few rain gauges in semi-arid, cloud-free lowland environments, the model overestimated flows. However, Mulligan and Burke (2005) found no relationship between relative prediction error and altitude, fog inputs or catchment average rainfall. Despite this limitation, Mulligan (2013b) argues that WaterWorld is still a useful model for examining the effect of climate and land use changes on water balance (and runoff) in comparison to a baseline simulation as opposed to predicting the exact magnitude of water balance or runoff at a specific point.

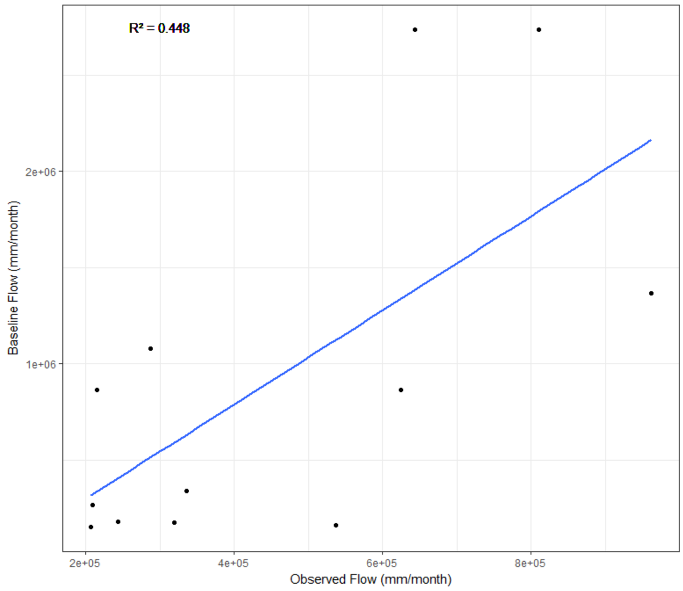

Figure 5-29: Correlation between the observed (data from RivDIS, (Vorosmarty et al., 1998)) and baseline values.

Validation of the model using only one gauging station can be seen as insufficient when considering such a large area and heterogeneous landscape. A lack of access to high-quality, long-term hydrological records are major limitations in most hydrological studies in this region, leading to uncertainties in the results. Data from other gauging stations could not be obtained.

However, by visually comparing the discharge graph at Mutonga (coordinates: -0.37, 38) presented in Sood *et al.* (2017), which is shown in Figure 5-30, it is clear that the WaterWorld model more accurately projects flows in the Upper Tana basin. The baseline annual runoff for Mutonga from WaterWorld is $69m^3s^{-1}$. Furthermore, as stated in the model description (Section 2), WaterWorld is predominantly a water balance model rather than a rainfall-runoff model (Mulligan, 2013b).

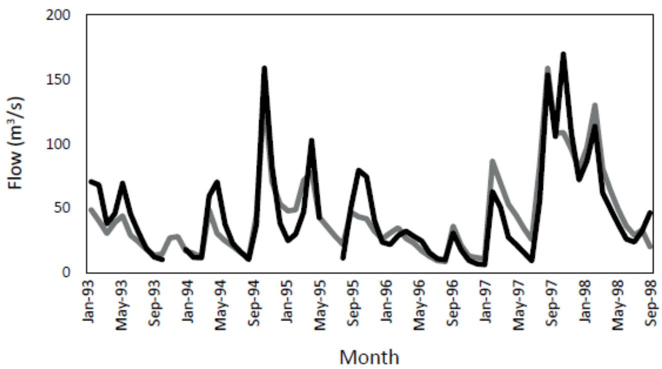

Figure 5-30: Black lines show the observed values from the Mutonga gauging station from Sood et al. (2017). The grey lines show their simulated values.

5.5.6 Water Security Implications

In addition to considering water availability, it is also important to consider the spatial variations in water demand. Just as water supply varies throughout the Tana River Basin, so does water demand. Figure 1-1 shows the major towns in and around the basin. Most towns are located in the upper Tana Basin, where rainfall is highest. The town of Garissa is located on the mid-reaches of the river. These populous regions are likely to have higher water demands. Kenya also has a rapidly urbanising population (Ndung'u *et al.*, 2011), suggesting that water demand in these areas is likely to increase in the future; supporting the importance of looking more at these regions. The National Spatial Plan (GoK, 2017) names Garissa and other towns within the Tana River Basin as important areas to develop economically. This will increase the population and the pressure on water resources in these areas.

The districts in the basin with the highest populations (Kenya Central Bureau of Statistics, based on 2005 values) are presented in Table 5-6. Figures 5-23 and 5-27, which showed the spread of GCM results for changes to water balance and water stress averaged within district boundaries, shows that all of the districts in the table below have a high GCM uncertainty.

Table 5-6: The most populous districts of the Tana River Basin (population data from the Kenya Central Bureau of Statistics, 2005)

District	**Population**	**Area (km²)**
Machakos	906,644	6,281
Kiambu	744,010	1,324
Nyeri	661,156	3,356
Thika	645,713	1,960
Meru North	604,050	3,942
Kitui	515,422	20,402

The National Water Master Plan (JICA, 2013) states that water demand is likely to substantially outweigh potential increases in water supply. Due to population growth, development and increases in agriculture, the water demand in the Tana catchment area is projected to increase to 8,241 million cubic metres (MCM) per year by 2030, from 891 MCM/year in 2010 (JICA, 2013). By contrast, the same report only projects increases in available water resources of 20% by 2030 based on modelling results from Nakaegawa and Wachana (2012).

Kenya experiences conflict and competition between population groups over variable and unpredictable resources like water (Fisher *et al.*, 2016). However, this study cannot consider the socio-economically defined access to water resources, which is still important in developing countries like Kenya. Additional analysis with political and socio-economic datasets would be necessary to investigate this water demand fully. However, the water stress results presented here provide a good estimate of the particular areas of concern.

5.6 Chapter Summary

This chapter has examined the changes in water balance, evapotranspiration and water stress with climate change, using the WaterWorld model. Results derived for 2 future time horizons, the 2050s and 2070s, were compared to the 1950-2000 baseline. The results show significant changes to water balance, largely as a consequence of increased rainfall, which was presented in Chapter 3. Changes are comparable under the 4 RCPs, but vary greatly between individual GCMs.

Reductions in basin-average water balance are possible in the dry seasons, whereas large increases are likely in the rainy seasons. Some districts have been identified where the spread of GCM results for changes in water balance are narrow. In these areas, the results can be seen as more certain. At the Garissa gauging station, an average annual increase in runoff (accumulated water balance) of 8-21% is projected using the multi-model mean for the 2050s.

Uncertainties in the projections of water balance change lead to a wide range of possible changes for water resources, even under the same RCP. The WaterWorld model has been shown to have limitations, which must be considered alongside the results. These limitations include the inability to consider groundwater flows or inter-annual variability. Challenges of water resources management in Africa also encompass a range of social and engineering dimensions.

The following chapter (Chapter 5) examines projected changes to the terrestrial biodiversity of the Tana River Basin as a result of climate change, using data from the Wallace Initiative database. The latter part of Chapter 6 will then combine the results from the different sectors (water, biodiversity and agriculture) to produce a multi-sectoral assessment of the impacts of climate change on the Tana River Basin.

Chapter 6 Impacts of Climate Change on the Terrestrial Biodiversity of the Tana River Basin

6.1 Introduction

The impacts of climate change on biodiversity are expected to be particularly severe, both at the global scale and across Africa. High biodiversity increases the stability of ecosystems and therefore maintaining it can increase the resilience of these ecosystems. This chapter will discuss the methodology for examining changes to Tana River Basin species (presented in Section 3), before taxonomic level and individual case study species results are presented and discussed. This chapter will largely focus on changes to biodiversity by the 2050s (for taxa level results which are presented in Section 4) or degrees of warming (for the case study species presented in Section 5). This addresses Objective Ic (impacts) and Objective IV (uncertainty). Changes to species distribution are compared to the current protected area (PA) network to see whether this is sufficient for protecting a range of species in the future.

6.2 Threats to the Biodiversity of the Tana River Basin

In addition to climate change, the biodiversity of the Tana River Basin is currently under threat from a myriad of other sources. As no threat acts in isolation, climate change must be considered in combination with these other stressors, both natural and human-induced. Hughes (1984) explained that the development of the Tana River Basin has been central to Kenya's development policies since its independence in 1963. Therefore, significant human-induced pressures on biodiversity are already present within the basin. Ojwang' *et al.* (2017) mapped the hotspots of human-wildlife conflict across Kenya. Several hotspots are found in the Tana River Basin, including around the Tana River Primate Reserve and coastal delta region.

6.2.1 Large-Scale Development Projects

Despite semi-arid conditions, the lower catchment is seen as suitable for development (which is discussed in more detail in Chapter 6, Section 4.6). Several large-scale irrigation projects have been proposed, with several focusing on the Tana Delta region. The lower basin has been identified by the Government of Kenya as underutilised for irrigation (Baker *et al.*, 2015) and many of the current irrigation schemes are found in the upper basin. Two major irrigation schemes, Hola (for cotton and maize) and Bura (for rice), already exist in the lower basin, but many more are planned. Hamerlynck *et al.* (2012) go so far as to argue that these large-scale projects are the greatest threat to the endangered primates of the lower Tana River Basin. However, the previous projects have been of limited success. An example is the Tana Delta Irrigation Project (TDIP). The project received a large amount of criticism for its Environmental Impact Assessment (EIA), as the Tana and Athi Rivers Development Authority refused to acknowledge the findings of the EIA and continued with the project. However, the TDIP encountered problems during the El Nino event of 1997-8 (Hamerlynck *et al.*, 2010). Arevalo *et al.* (2014) examined the conflicts of another project, the Bedford Biofuels project, and showed that the land functions as a wildlife corridor between the Tana Delta and the Tsavo East National Park, suggesting that developing large scale agriculture in this area would have a negative effect on biodiversity movement. Baker *et al.* (2015) estimated that nearly another 300,000 ha of large-scale irrigation is planned for the Tana River Basin by 2030.

In addition to agricultural projects, other economic development projects threaten the wildlife. The Lamu Port –South Sudan-Ethiopia Transport (LAPSSET) corridor plan is a major development project and includes the building of highways, railways and an oil pipeline across Kenya. This project includes large roads and a railway line that cross the basin, cutting through important wildlife areas. The LAPSSET corridor has been designed to spur urban growth by improving connections in the country. Key urban centres in the Tana Basin that are expected to grow because of this project include Garissa along the mid-reaches of the river and Meru in the north (GoK, 2017). However, this project is currently behind schedule. The LAPSSET corridor is but one example of the development projects set out in the Vision 2030 (GoK, 2007).

6.2.2 Ineffective Conservation Management

Issues arise due to competing land uses and the encroachment of human settlements on important conservation areas. For example, Hamerlynck *et al.* (2010) showed that habitat loss continued within the Tana River Primate Reserve as local communities who had been displaced by the reserve's creation continued to exploit the forest's resources. Despite having long-established PAs for wildlife, a significant proportion of Kenya's wildlife exists outside of these and is still exposed to increased pressures from human activity. Ojwang' *et al.* (2017) also argued that the current PAs may not be adequate to preserve the species, as their creation did not consider the full requirements of many wildlife species that they are aiming to protect. Many PAs are too small to include all elements of the ecosystem which are important to the wildlife.

6.2.3 Dam Construction

Highly modified rivers are more sensitive to changes and take longer to recover from shocks. The Tana River has already been modified through dam construction and research has linked the reduction in floodplain forests to reductions in flooding following this dam construction (Maingi and Marsh, 2002). In addition, dams have been linked to the transmission of waterborne diseases in many African countries including Kenya (Finlayson *et al.*, 2005).

6.3 The Wallace Initiative

6.3.1 MaxEnt (Maximum Entropy) Modelling

The SDM MaxEnt (Phillips *et al.*, 2006) has been utilised in the Wallace Initiative and uses a climate envelope approach. MaxEnt has been found to perform well compared to other species distribution modelling methods (Elith *et al.*, 2006; Wisz *et al.*, 2008; Giovanelli *et al.*, 2010). MaxEnt modelling can be conducted with only occurrence (presence-only) data and estimates the probability of a species' occurrence based on the distribution of maximum entropy (i.e. the distribution that is closest to uniform) under various environmental conditions (Phillips *et al.*, 2006; Phillips and Elith, 2013). Making use of presence-only datasets is extremely useful. As shown by Elith *et al.* (2011), most species records are based only on occurrence, rather than both presence and absence. Therefore, MaxEnt can make use of a greater number of species records. MaxEnt has been shown to perform well even with low sample sizes (Hernandez *et al.*, 2006). This is supported by Wisz *et al.* (2008), who compared a range of models with low sample sizes and found that MaxEnt outperformed most other models tested. In addition, the model output is continuous, which allows for the examination of the probability of presence in different cells.

MaxEnt uses both the environmental information and species occurrence records to generate a probability distribution of the species' current distribution across the study area. This step extracts the relationship between the environmental variables (e.g. precipitation or temperature) and the species' occurrence and trains the model to create a probabilistic distribution based on this relationship (Warren *et al.*, 2013b). The relationship is then projected onto current climate (1961-1990 for this application) to map the potential geographic distribution of species across all land areas. Each grid cell has a predicted suitability of conditions for the species of interest. The suitability is a function of the bioclimatic variables for that grid cell.

6.3.2 The Wallace Initiative

The Wallace Initiative was started to assess climate change impacts on the distribution of species globally. This work has helped inform the development of conservation plans, possible extinction risks and refugia for wildlife (Price *et al.*, 2013; Warren *et al.*, 2013b). Biodiversity records for use in the model were obtained from the Global Biodiversity Information Facility (GBIF). GBIF is an open-source database containing records of when and where species have been recorded around the world (Yesson *et al.*, 2007). The GBIF database contains an extremely large set of occurrence records and therefore inaccuracies are possible. To account for inaccuracies, the GBIF data (GBIF.org, 2015) was cleaned before it was used in the Wallace Initiative modelling. This cleaning process consisted of three steps. First, records with no location data were removed, including any records whose coordinates did not fall on land. Then, occurrence data which did not match the species' country of origin were taken out and, finally, points which fell outside species niche requirements were removed (Warren *et al.*, 2013b).

The Wallace Initiative contains information about the potential future climate space for various climate change scenarios for three 30-year periods. Climate data were the post-processed outputs of ClimGen (Osborn *et al.* (2016), described in Chapter 4, Section 4.2). Four climate indictors were extracted from ClimGen: monthly mean temperature, monthly maximum temperature, monthly minimum temperature and precipitation. The 30-year time slices are centred on 2025, 2055 and 2085. The monthly climate outputs were averaged over these time periods. The AVOID climate change scenarios were used for this work. These are versions of the RCPs produced for the UK Government as part of their AVOID project (Gohar and Lowe, 2009). The ClimGen outputs were post-processed to create the bioclimatic indices needed for the MaxEnt model. These eight bioclimatic indices are: (1) average maximum temperature of the warmest month of the year, (2) the average minimum temperature of the coldest month of the year, (3) annual mean temperature, (4) temperature seasonality, (5) total annual rainfall, (6) rainfall seasonality, (7) rainfall of the wettest quarter and (8) rainfall of the driest quarter (Warren *et al.*, 2013b). Limiting to eight indices reduces the likelihood of overfitting and minimizes potential issues with autocorrelation. Although these 8 parameters might not be the best for every species included in the database, they are generally considered to be satisfactory for a large range of species.

The default settings were used for the MaxEnt modelling for the Wallace Initiative. These settings were optimised for large groups of species globally (Phillips *et al.*, 2006) so are appropriate for this research. The distributions were then clipped to the bio-geographic zones that the initial species information was derived from, including a buffer to minimise commission errors (Warren *et al.*, 2013b).

The Wallace Initiative work employs different dispersal scenarios. The dispersal rate refers to the average long-term shift of a species' entire range (Warren *et al.*, 2013b). Many previous species distribution modelling studies used two dispersal rates to examine potential changes: no dispersal and full dispersal. However, Warren *et al.* (2013b) deemed full dispersal to be unrealistic, due to factors such as barriers to species movement, a lack of instantly available suitable habitats and the typical dynamics of range shifts that has previously been observed. Therefore, alternative dispersal scenarios were developed for the Wallace Initiative work: no dispersal, realistic dispersal and optimistic dispersal. The realistic and optimistic dispersal rates were developed from a review of the literature and vary for each taxon (Price *et al.,* 2013). Realistic dispersal represents the average dispersal value from the literature, whereas optimistic represents the highest value stated. All dispersal scenarios were restricted to connecting land areas (i.e. species could not move across oceans). Table 6-1 shows the species movement rates under each of the 3 different dispersal scenarios, adapted from Warren *et al.* (2013b).

Table 6-1: Dispersal rates used in the Wallace Initiative. Adapted from Warren et al. (2013b).

	Dispersal Mechanism		
TAXA	**No Dispersal Km/yr**	**Realistic Dispersal Km/yr**	**Optimistic Dispersal Km/yr**
Amphibia	-	0.1	0.5
Aves	-	1.5	3
Mammalia	-	1.5	3
Reptilia	-	0.1	0.5
Plantae	-	0.1	0.5

This research focuses on 'no dispersal' and 'realistic dispersal'. The realistic dispersal rate has been regarded as the most likely scenario.

Moreover, the Wallace Initiative can identify corridors of appropriate habitat along which the species can move. This could inform conservation policies by showing where resources should be focused; i.e. by providing for species' movement along these corridors. Pearson and Dawson (2003) demonstrate the importance of this, showing that the ability to migrate is also affected by the landscape over which the individual is trying to move. Habitat fragmentation would provide barriers to dispersal that have not been encountered during previous mass migrations.

The Wallace Initiative can be used to examine changes at a taxa level. For instance, 'areas of concern' (AOC) or 'refugia' can be identified for the different taxa (i.e. aves, amphibia, mammalia, reptilia, plantae). AOCs are defined as areas that become climatically unsuitable for at least 75% of the species studied, whereas refugia are areas where more than 75% of the species could remain.

In addition, individual species can be examined. The latest version of the Wallace Initiative (v.3) (Warren *et al.*, 2018b) provided the information on the individual species. Wallace v.3 contains data on around 100,000 plants, mammals, birds, reptiles, amphibians and some insects. The spatial resolution of the projected species distributions is 20km x 20km. Data for future distributions is based on results from the 21 GCMs with global warming levels of 1.5°, 2°, 2.7°, 3.2° and 4.5°C above pre-industrial levels. A high-end scenario of 6°C is also available but has not been considered in this research. These temperatures were chosen by Warren *et al.* (2018b) to fit in with global temperature targets. Warming of 1.5°C and 2°C are included in the UNFCCC Paris Accord goals, 2.7°C and 3.2°C correspond to the NDCs (Rogelj *et al.*, 2016; climateactiontracker.org, 2018) and 4.5°C represents a business as usual (BAU) scenario. The BAU scenario would arise if the Paris Agreement is not met and GHG emissions continue to rise (Collins *et al.*, 2013). These levels of warming provide a range of scenarios, with the BAU scenario providing the 'worst case' scenario.

6.3.2.1 Case Study Species

Some important species of flora and fauna were highlighted during the Literature Review (Chapter 2, Section 7), many of these are important for tourism or are particularly vulnerable. The animals identified as important for tourism include the African elephant, lion, hippopotamus and buffalo, which are seen as large, charismatic species. This makes them favoured by conservation planners due to their importance to the tourism industry. Further species were sourced from the

IUCN Red List website (IUCN, 2014). Lists of species native to Kenya which fell into the IUCN Red List categories CR (critically endangered), EN (endangered), VU (vulnerable) and NT (near threatened) and LR (lower risk) for each of the five taxa were obtained. A total of 140 native species of these taxa fall into the CR or EN categories. Another 303 native species are classed as VU, LR or NT. All of the species present in the Wallace Initiative database and found within the Tana River Basin (based on the current climate maps from the Wallace Initiative) have been analysed. Of the 140 CR or EN species, only 14 were present in the Wallace Initiative database and found within the Tana River Basin. Of the 303 VU, LR or NT species, 47 were present in the database and found within the basin.

In addition, animal species (mammals, birds, reptiles and amphibians) which are classified as LC (least concern) but were known to be threatened by climate change, agricultural development and/or wetland degradation (also obtained from information on the IUCN Red List website) have also been analysed. 55 LC mammals, birds, amphibians and reptiles native to Kenya are listed as 'threatened by climate change and severe weather' on the IUCN Red List (2018). Another 108 are listed as threatened by agriculture (IUCN, 2018).

The numbers of species analysed by taxa are presented in Table 6-2. A full list of these species and the IUCN Red List (IUCN, 2014) status of each species can be found in Appendix IV. Not all species identified are present in the Wallace Initiative records. The species absent from the database include the endemic primates; the Tana River red colobus monkey and the Tana River mangabey. As these species could not be directly examined, their food sources were analysed instead. Wieczkowski and Kinnaird (2008) provided a list of the six most common species consumed by the primates. Out of these six species, five were present in the Wallace v.3 database.

Table 6-2: Numbers of individual species selected for the case study, by taxa

Taxa	**Number of species**
Aves	34
Amphibia	5
Mammalia	22
Plantae	31
Reptilia	4
TOTAL	**96**

6.4 Taxa Level Results

This section will examine the current species richness (6.4.1), identify particular areas of concern and refugia (6.4.2), including comparing these locations to the current PA network, and then quantify the proportion of species remaining within the basin for the taxa under a changing climate (6.4.3). The majority of results focus on the 2050s, but some graphs show the changes over time (considering the 2020s, 2050s and 2080s).

6.4.1 Current Species Richness by Taxa

Figure 6-1 shows the spatial distribution of the different taxa under current climate conditions according to the model. The highest values of species richness for all taxa currently are seen to be in the northwest and southeast of the basin, in the mountainous, Upper Tana region and the lower Tana Delta respectively. The mountainous areas support a large variety of plants. By contrast, the lower reaches of the river and the delta region supports the highest number of reptiles. The basin currently has a particularly high number of bird and plants.

The semi-arid floodplains in the centre of the basin have a relatively low biodiversity at the scale studied here. However, small areas of floodplain forest that maintain higher levels of biodiversity may be sub-grid scale, such as those investigated by Hughes (1984).

As all taxa show the same broad spatial patterns of highest biodiversity, the mountains and the delta are important areas for conservation. The current PA network covers many cells with a high species richness for all five taxa; for instance the Mount Kenya National Park and National Forest in the Upper Tana and the Lower Tana Delta Conservation Trust and Hanshak-Nyongoro Community Conservancy in the southeast. However, there are also other cells with a high species richness according to the model which are not covered by the PAs. There are cells in the south of the basin which have a high number of amphibians and reptiles but are not covered by the PAs. These lie in between the PAs in the delta and the Tsavo East National Park in the southwest of the basin. Similarly, areas around the PAs in the north of the basin show a particularly high plant and mammal richness. These maps show the suitability of the area for a large number of species. However, land use changes and other pressures on the ecosystems may or may not have allowed them to persist in these areas.

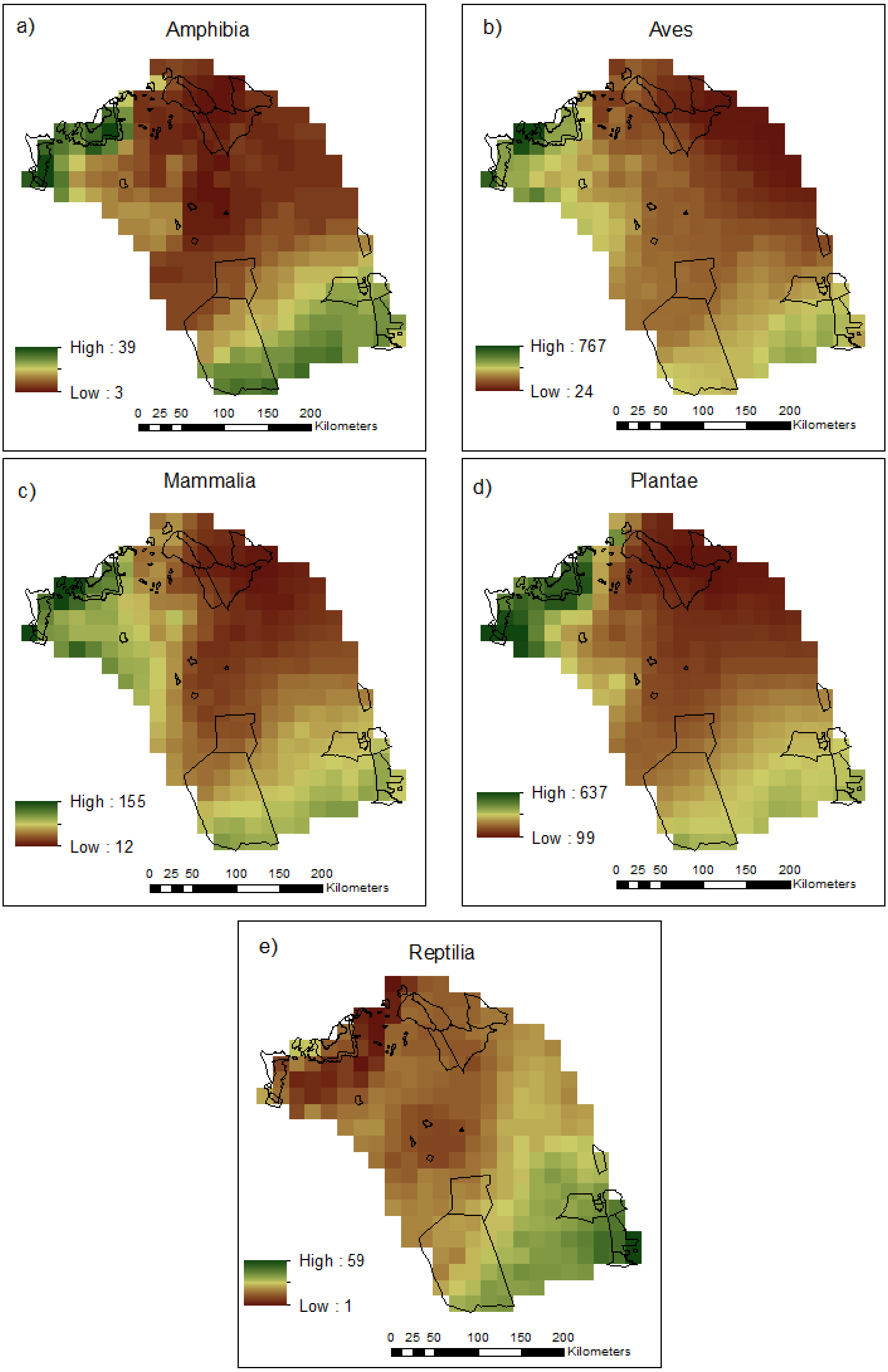

Figure 6-1: current modelled species richness for (a) amphibia; (b) aves; (c) mammalia; (d) plantae and (e) reptilia. The black outlines show the locations of PAs, which can be compared to the species richness according to the model.

6.4.2 Identifying Potential Areas of Concern and Refugia

Here, a refugium is identified in a grid cell only if at least 15 of the 21 GCMs agree on its existence. There are no large areas where most models agree on the existence of AOCs. However, there are substantial areas where most models agree would be refugia for the different taxa. For mammals and birds, both the no dispersal and realistic dispersal scenarios have been examined. However, at the spatial scale used here, plants, amphibians and reptiles cannot move a large enough distance within the time horizon to see a difference between the realistic and no dispersal scenarios. Therefore, there is no advantage in considering both and only ‘no dispersal’ was chosen.

Figure 6-2 shows the number of cells in the basin identified as refugia by the 2050s. Fewer cells are considered refugia under RCP8.5 and most under RCP2.6. In most cases, RCP6.0 shows higher values than RCP4.5. For this time horizon, the temperature increase is greater for RCP4.5 than RCP6.0. For mammals and birds, there are clear differences in the projected refugia for the different dispersal scenarios, with realistic dispersal resulting in more cells being considered refugia.

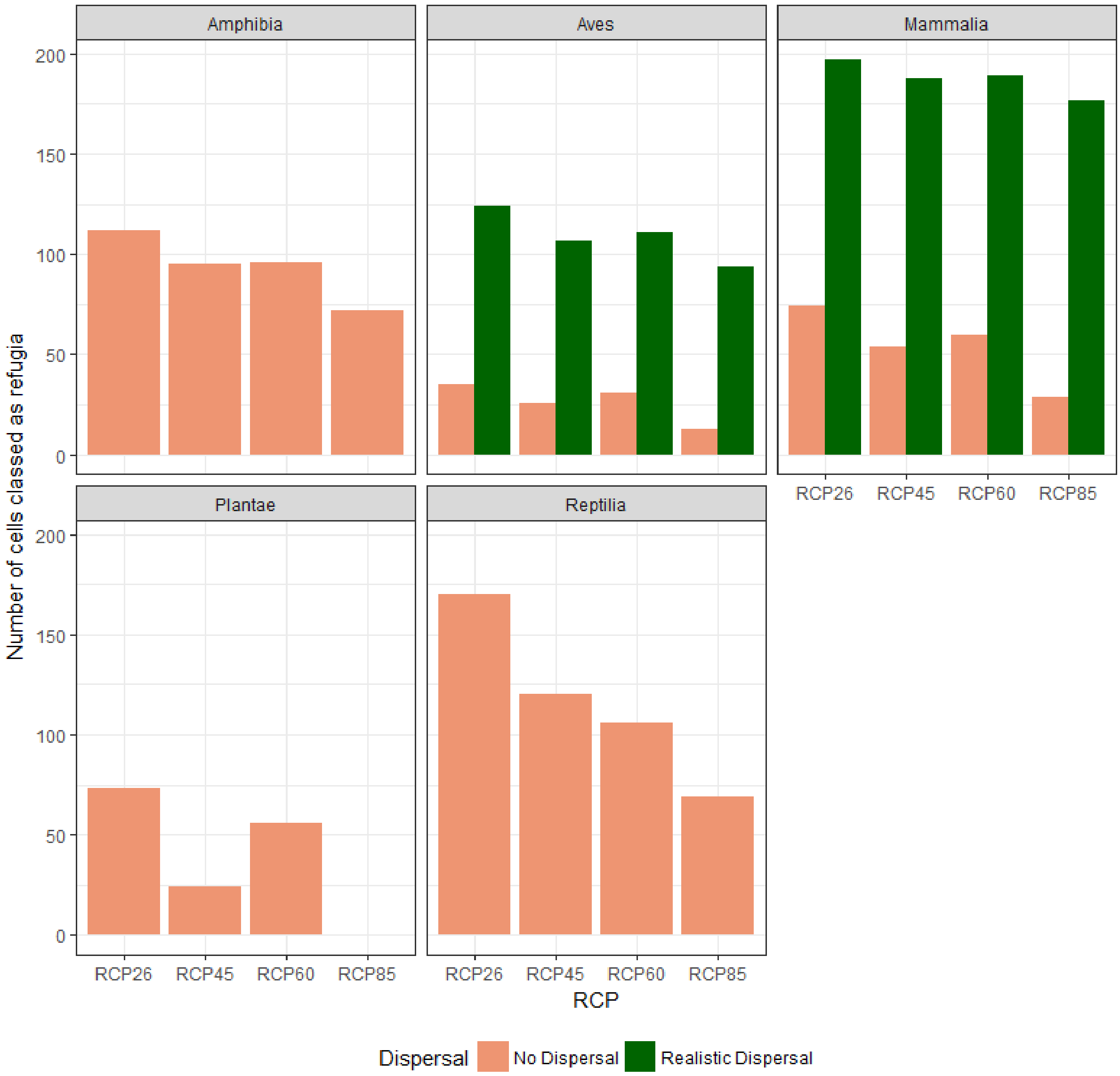

Figure 6-2: Number of cells classed as refugia by taxa for the 2050s for the different taxa and RCPs. Aves and Mammalia show the difference between the two dispersal scenarios. . Data are presented as the mean across 21 alternative climate models and the mean across the study area.

6.4.2.1 Refugia for all Taxa

Combining the results for the different taxa and models can be used to reduce the uncertainty associated with individual taxa and increase confidence in the model results. Furthermore, if a cell is a refugium for all taxa, it is more likely to be an important area to focus conservation efforts. However, as plants showed some different patterns to animals, they are shown individually. Finding refugia for all animals was achieved by adding together the number of models that agreed for each animal taxa for each cell within the basin. For animals, the highest number possible is 84, showing that all the models agreed this was a refugium for the four animal taxa. For plants, the highest possible number in agreement is 21.

Figures 6-3 and 6-4 show the agreement on refugia for plants and animals (birds, mammals, amphibians and reptiles combined) respectively for the 2050s under RCP2.6 and RCP8.5 conditions. For RCP2.6, there are fairly large areas of the basin that the models agree would be a refugium for animals and plants. Potential refugia for plants occur in the mountains in the north of the basin, along the main Tana River and at the coast in the Tana Delta region. Limited refugia exist for RCP8.5 for both plants and animals. Under these conditions, there are no cells where all the models project refugia for plants. This has important implications for the animals that are dependent upon specific plant species for food or habitats.

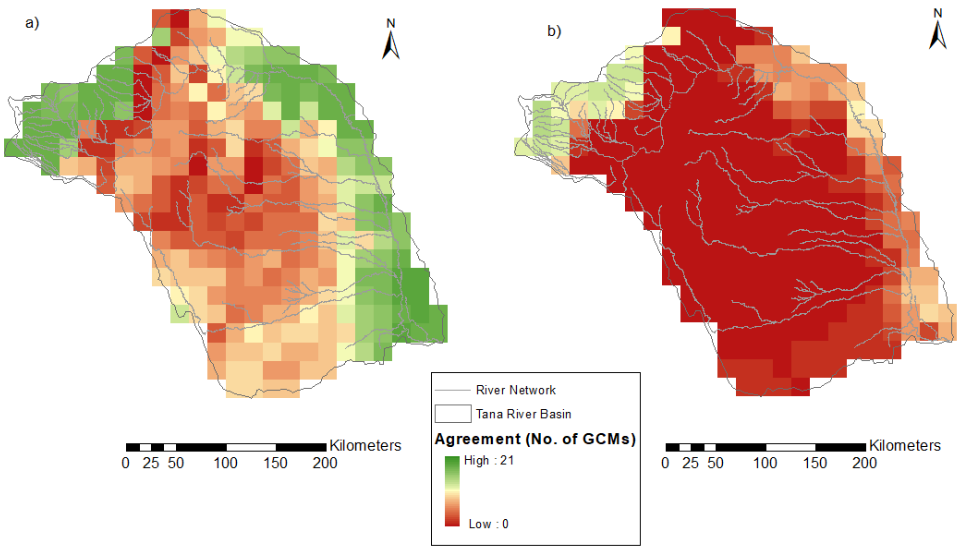

Figure 6-3: GCM agreement about refugia for plants for a) RCP2.6 and b) RCP8.5 for the 2050s. The highest number of GCMs possible is 21.

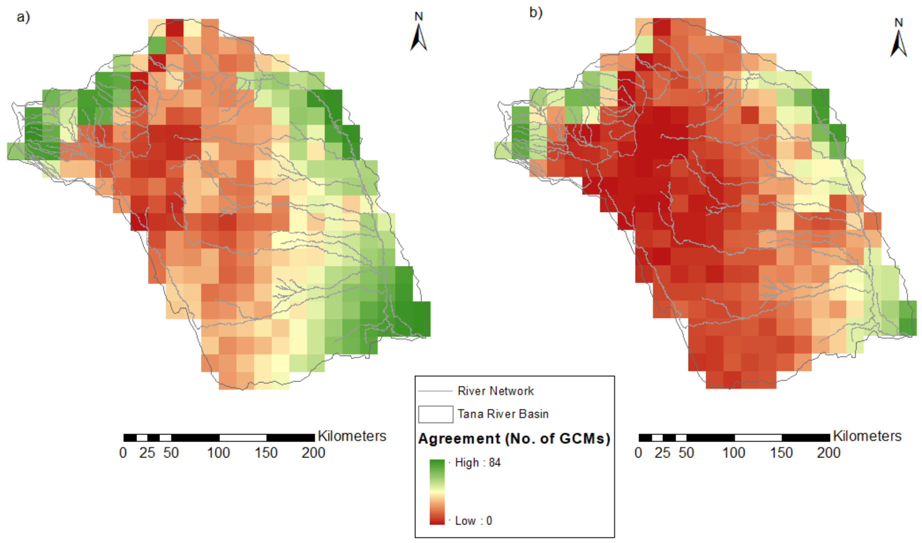

Figure 6-4: GCM agreement about refugia for all animals (mammals, birds, reptiles and amphibians) for a) RCP2.6 and b) RCP8.5. The total number of GCMs possible is 84. This shows no dispersal for the 2050s.

Figure 6-5 shows the agreement on the location of refugia for the four animal taxa under RCP2.6 conditions for the 2050s, when dispersal is not considered. Interestingly, a large proportion of the basin is projected to contain refugia for reptiles under these conditions. Figure 6-6 shows the situation for RCP8.5 conditions. As seen with the ‘all animals’ maps in Figure 5-4, fewer refugia are projected for the individual animal taxa under RCP8.5 conditions. There are large areas where no GCMs project refugia for mammals, amphibians and birds under RCP8.5 conditions, when dispersal is not considered.

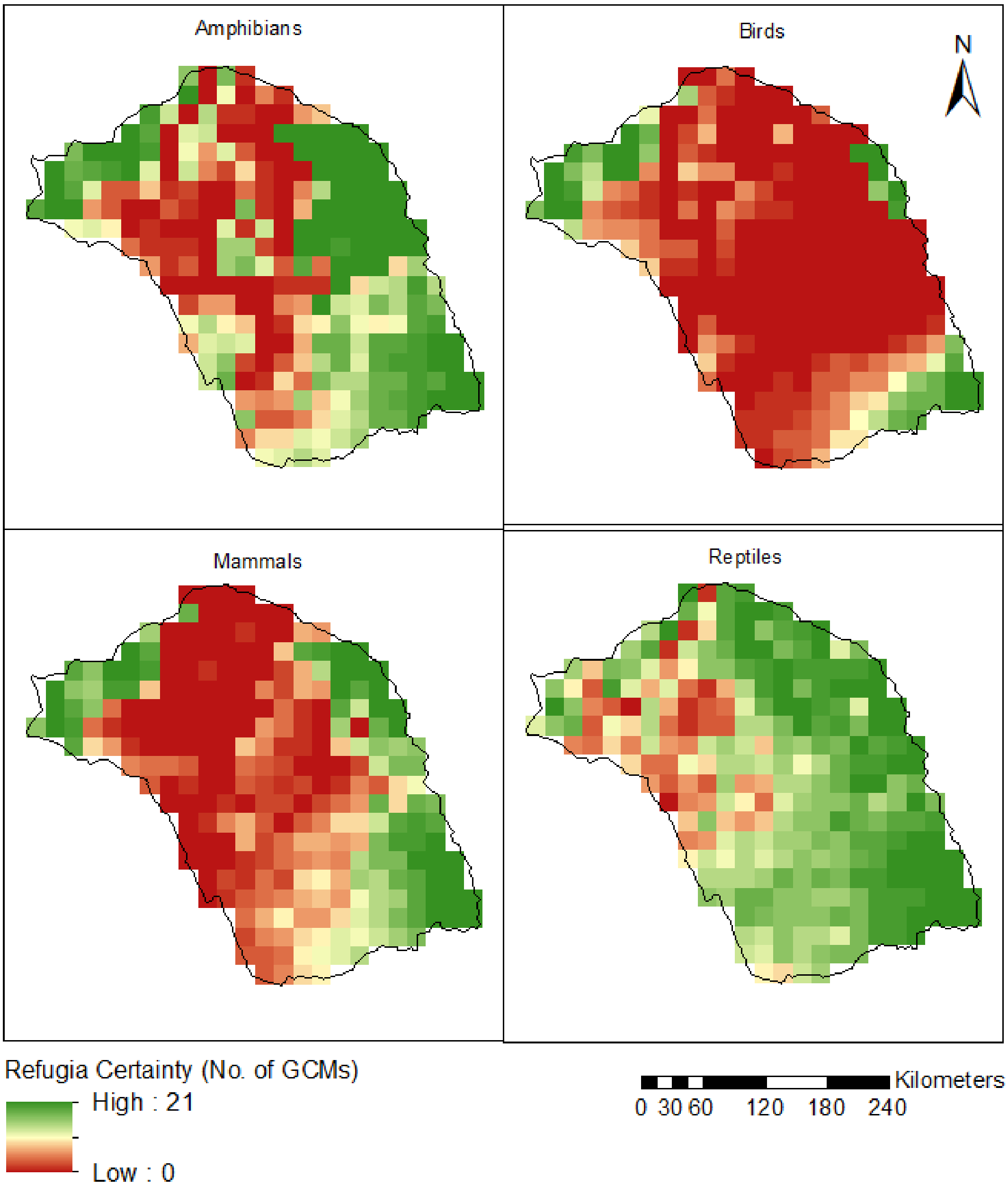

Figure 6-5: GCM agreement about refugia for the four different animal taxa. The total number of GCMs possible is 21. This shows no dispersal for the 2050s under RCP 2.6 conditions.

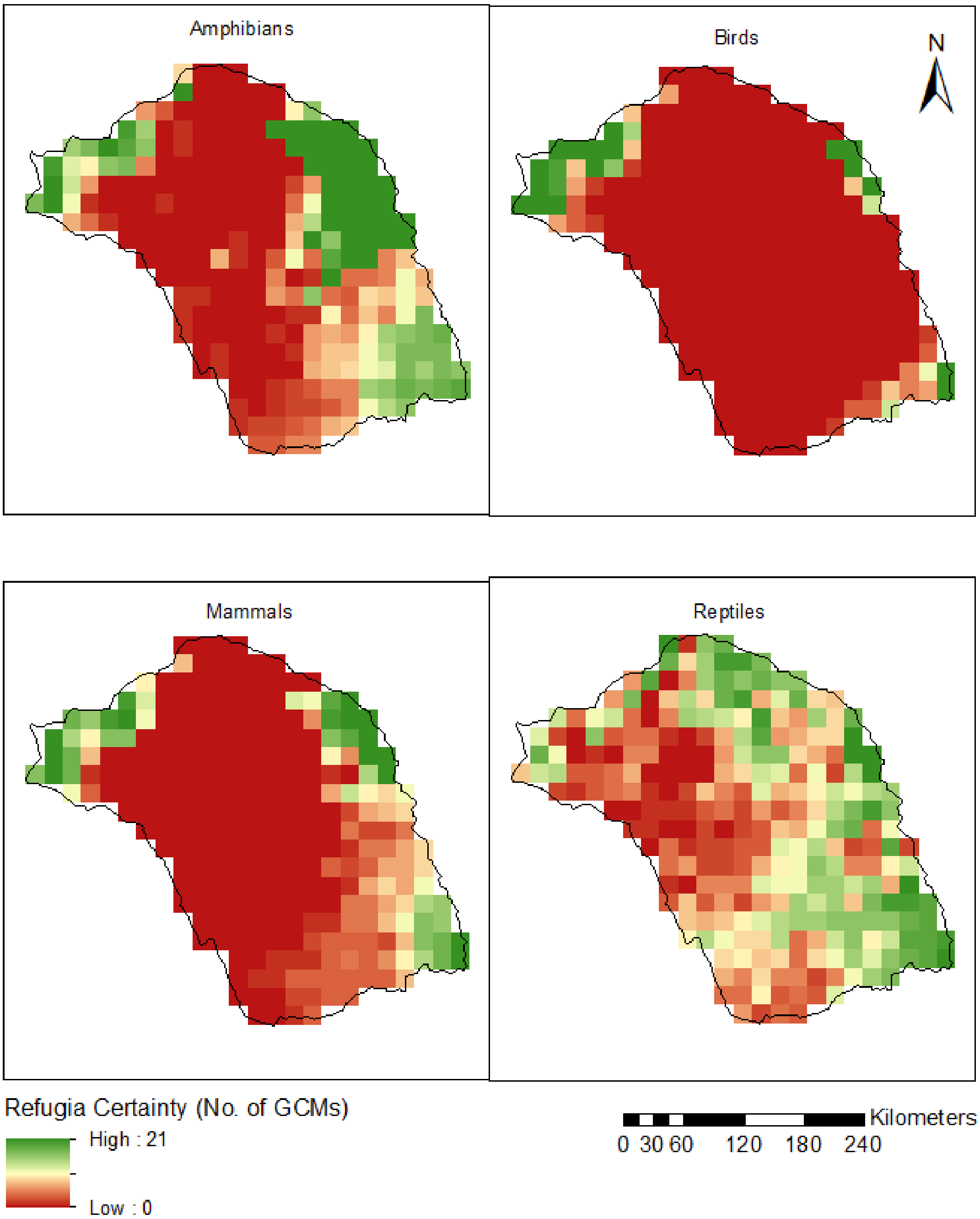

Figure 6-6: GCM agreement about refugia for the four different animal taxa. The total number of GCMs possible is 21. This shows no dispersal for the 2050s under RCP 8.5 conditions.

Figures 6-7 and 6-8 show the agreement between the GCMs over the location of refugia for mammals and birds with realistic dispersal, for RCP2.6 and RCP8.5 conditions respectively. A greater number of cells are projected to contain refugia for both RCPs when dispersal is considered. More refugia are projected for mammals than for birds under both RCPs when these species are able to disperse at realistic rates. In addition, the difference between the two RCPs is not as great when dispersal is allowed.

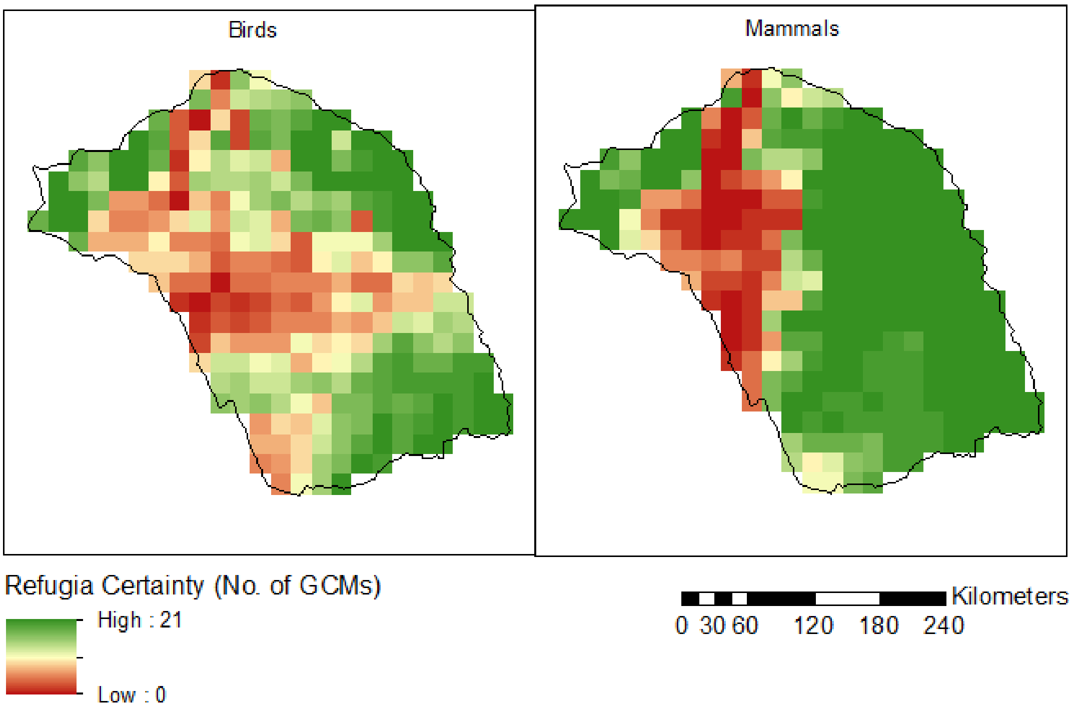

Figure 6-7: GCM agreement about refugia for birds and mammals. The total number of GCMs possible is 21. This shows realistic dispersal for the 2050s under RCP 2.6 conditions.

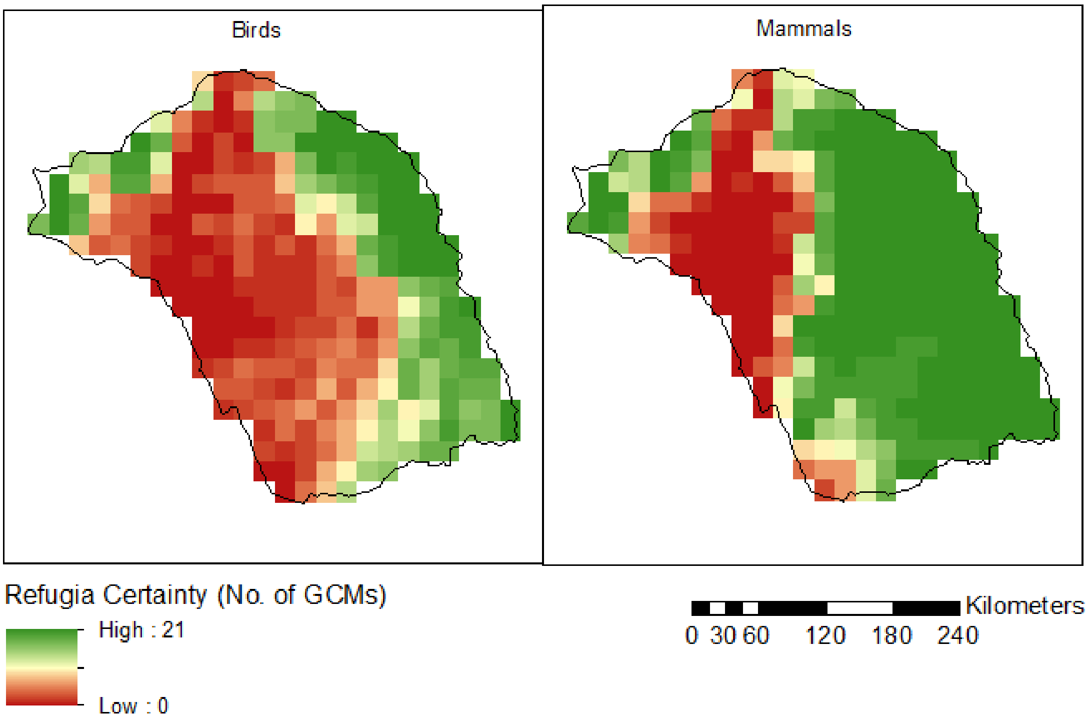

Figure 6-8: GCM agreement about refugia for birds and mammals. The total number of GCMs possible is 21. This shows realistic dispersal for the 2050s under RCP 8.5 conditions

6.4.2.2 Refugia in comparison to Protected Areas

Some refugia overlap with the existing PAs, particularly those in the mountains and in the Tana Delta, such as the Mount Kenya National Park and the Tana Delta Conservancy respectively. However, the Tsavo East PA in the southwest of the Tana Basin is not projected to be a refugium by the majority of models for either animals or plants. Figure 6-9 shows the number of GCMs in agreement for the PAs for all plants (assuming the species are not able to disperse) by the 2050s for RCP2.6 and RCP8.5. Under RCP2.6, more models project that the current PA network will contain refugia for plants. Under RCP2.6 conditions, the Mount Kenya National Park and PAs in the Tana Delta region (such as the Lower Tana Delta Conservation Trust and the Hanshak-Nyongoro Community Conservancy) are projected to contain refugia by most models. However, for RCP8.5, there is greater disagreement for all PAs. Under RCP8.5, fewer PAs are projected to contain refugia for plants by the different models. Around half of the PAs analysed are not projected to contain refugia for plants by any of the 21 GCMs with higher levels of warming. The Mount Kenya National Forest is the only PA projected to contain refugia for plants by over half of the GCMs under RCP8.5. Figure 6-10 also shows this information in map form so the location of the PAs can be easily seen and compared.

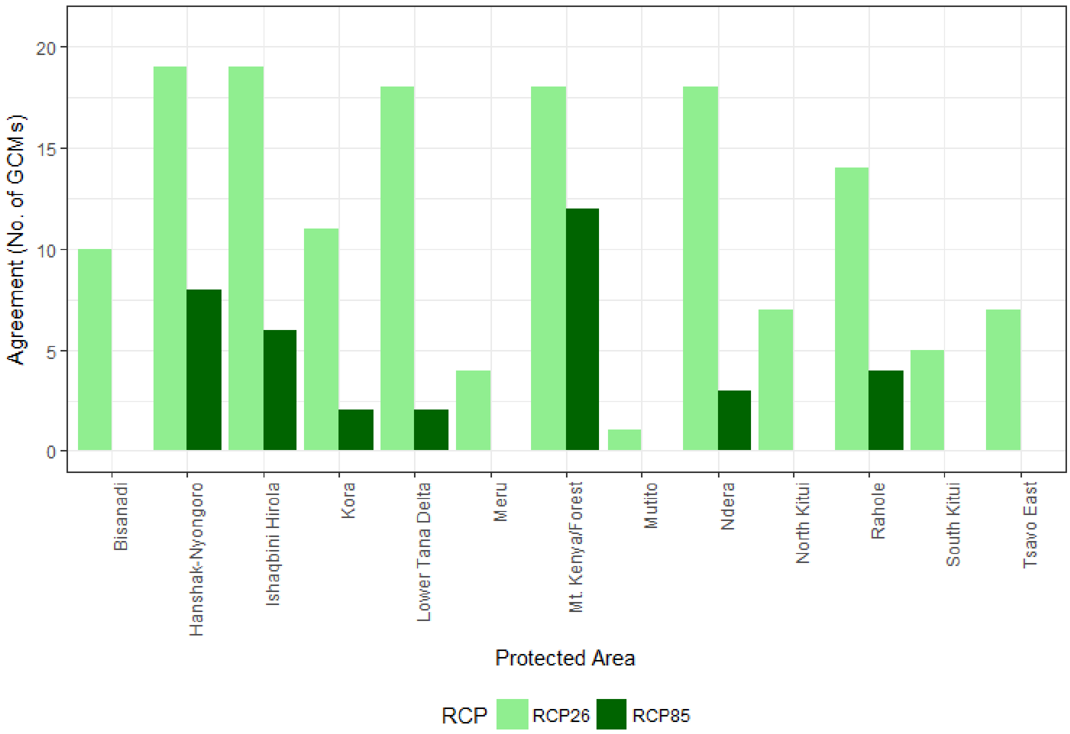

Figure 6-9: Number of models projecting that the PAs will contain refugia for plants by the 2050s under RCP2.6 conditions (light green) and RCP8.5 conditions (dark green). The highest number of possible models in agreement is 21.

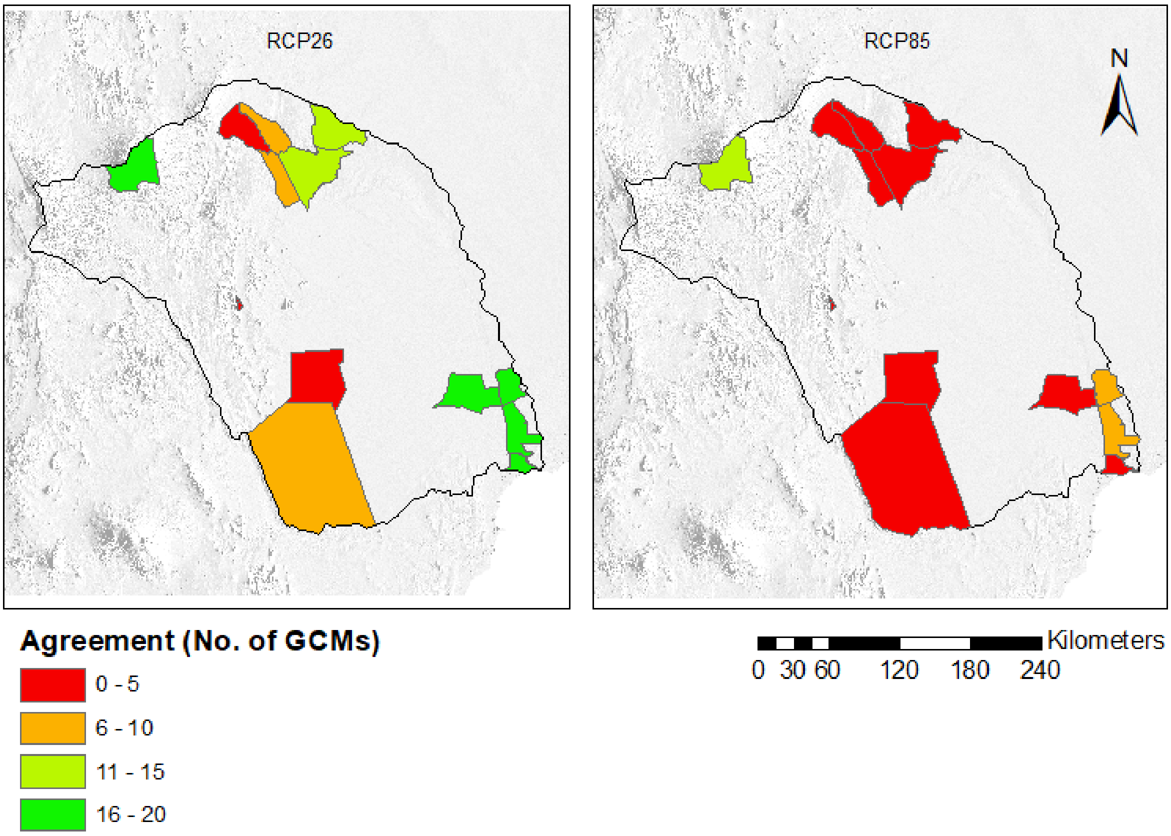

Figure 6-10: Number of GCMs projecting that the PAs would contain refugia for plants for RCP2.6 and RCP8.5 for the 2050s. The highest number of possible models in agreement is 21.

The difference between the two RCPs is not as pronounced for the four animal taxa. Figure 6-11 shows the number of GCMs projecting that the PAs will contain refugia for the four animal taxa under RCP2.6 and RCP8.5 conditions. For mammals and birds, the two different dispersal scenarios are shown (with ‘no dispersal’ in pink and ‘realistic dispersal’ shown in green). Corresponding maps for the four animal taxa individually can be found in Appendix III.

For all taxa, the Hanshak-Nyongoro Community Conservancy, Ishaqbini Hirola Community Conservancy and Lower Tana Delta Conservation Trust are projected to contain refugia by the majority of models under both RCPs. However, more models are in agreement for RCP2.6. There is a clear difference between the two dispersal scenarios for mammals and birds. In all cases, either the same or a greater number of GCMs project refugia within PAs when dispersal is included.

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Figure 6-11: Number of models projecting that the PAs will contain refugia for the four animal taxa by the 2050s under RCP2.6 (left) and RCP8.5 (right) conditions. Where appropriate, the different colours indicate the two different dispersal scenarios. The highest number of possible models in agreement is 21.

Figures 6-12 and 6-13 show the number of GCMs agreeing that PAs are projected to contain refugia for all animals (birds, mammals, amphibians and reptiles) for RCP2.6 and RCP8.5 respectively, without dispersal. As this is a combination of the four animal taxa, only the ‘no dispersal’ scenario is shown. By combining the taxa, it is possible to identify the PAs that are projected to contain refugia for a wide range of animals. Maps of refugia agreement compared to the PAs for birds and mammals with realistic dispersal can be found in Appendix III.

Figure 5-12 shows that for RCP2.6, the Hanshak-Nyongoro Community Conservancy, Ishaqbini Hirola Community Conservancy, Lower Tana Delta Conservation Trust and Ndera Community Conservancy are found to be refugium by all models. In addition, Kora, Rahole and Bisanadi (located in the north) are projected refugia by most models. Figure 6-13 shows that for RCP8.5, fewer PAs are considered refugia and no areas show full GCM agreement across the full PA. However, Hanshak-Nyongoro Community Conservancy, Ishaqbini Hirola Community Conservancy, Lower Tana Delta Conservation Trust and Ndera Community Conservancy are still projected refugia by most models.

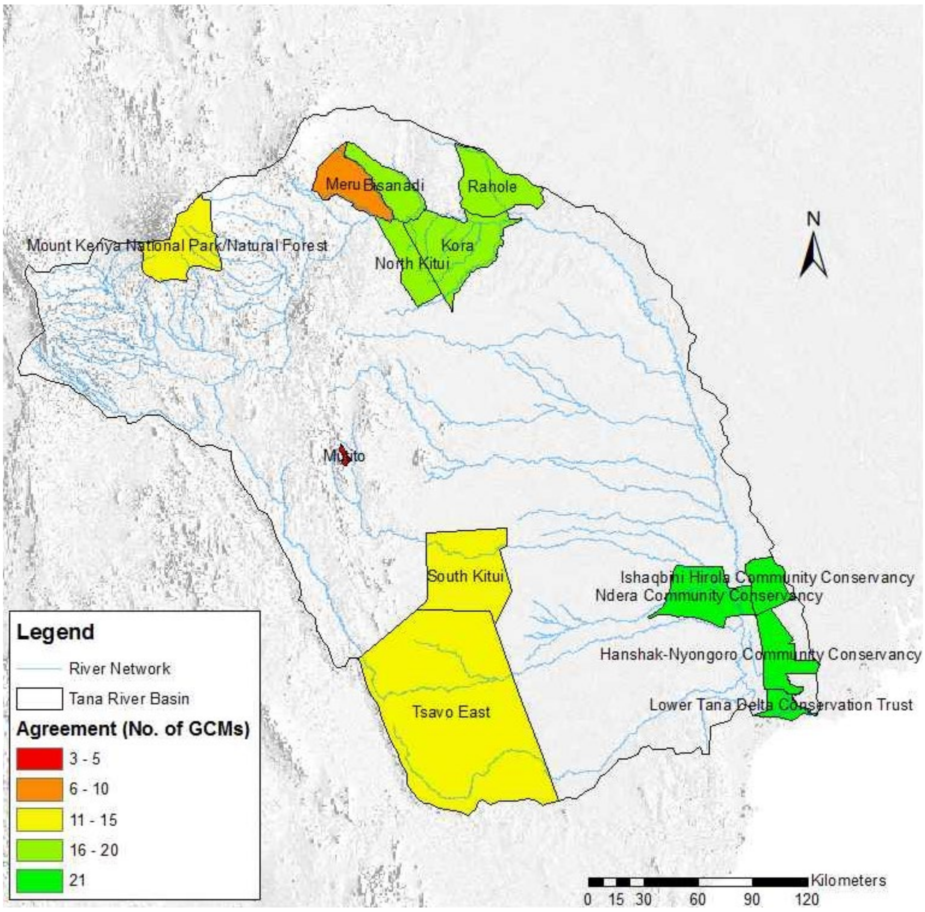

Figure 6-12: Number of GCMs projecting that a PA would be a refugium for animals for RCP2.6 assuming no dispersal for the 2050s. The highest number of possible models in agreement is 21.

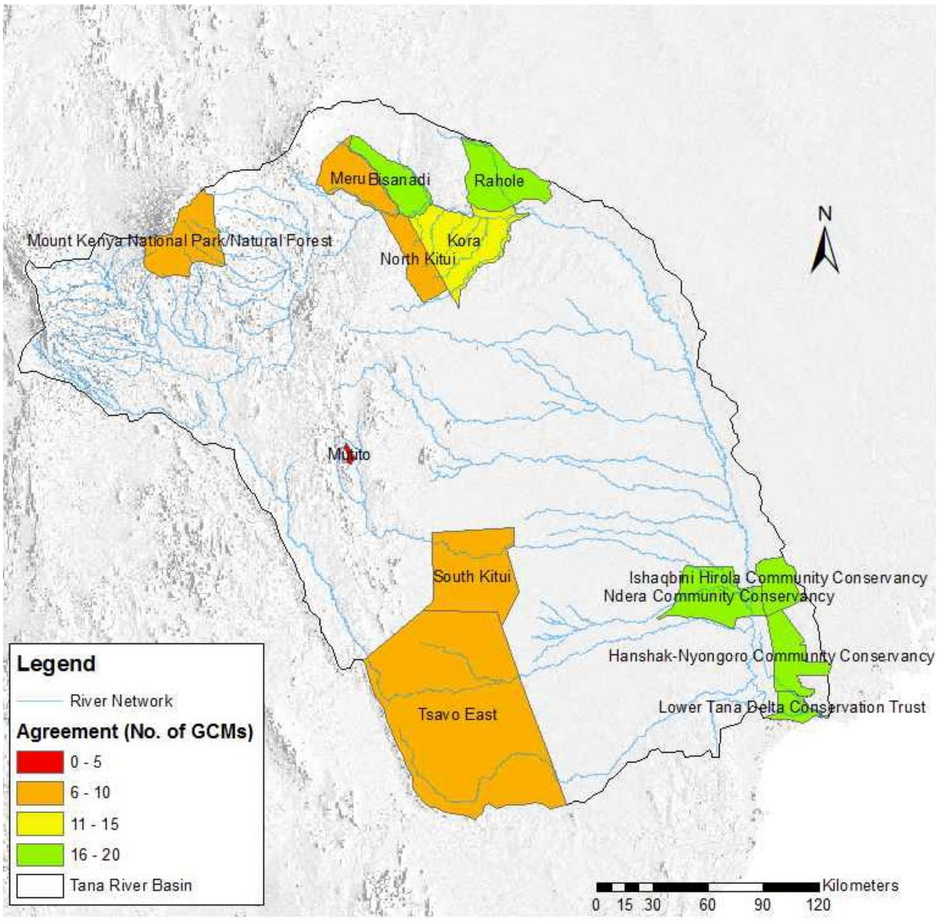

Figure 6-13: Number of GCMs projecting that a PA would be a refugium for animals for RCP8.5 assuming no dispersal for the 2050s. The highest number of possible models in agreement is 21.

6.4.2.3 Refugia for Birds in comparison to EBAs

There are two main endemic bird areas within the Tana River Basin, the Kenyan Mountains in the northwest and the East African coastal forests in the southeast. In the north of the basin, the EBA overlaps with existing PAs, namely the Mount Kenya National Park, Aberdare, Imenti or Upper Imenti and the smaller Nyambeni forest reserve. The EBA in the southern basin has little overlap with existing PAs. Figure 6-14 shows that these EBAs correspond well to the projected refugia in the basin, particularly for RCP2.6. It is likely that this is because the EBAs are located at the coast and in the mountains, where climates are relatively cooler. With RCP8.5, the East African coastal forests EBA is not projected to be a refugium by the majority of GCMs.

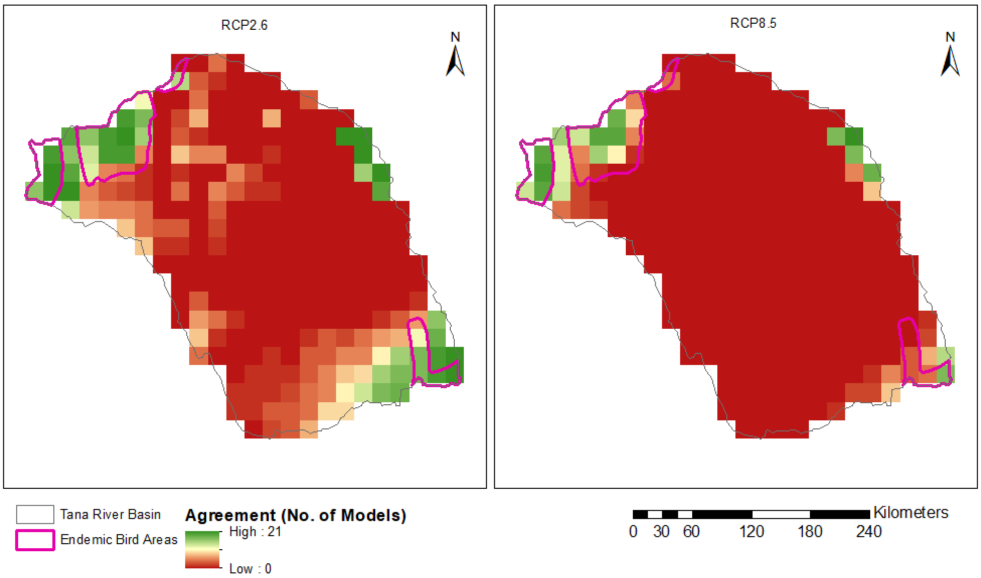

Figure 6-14: Endemic Bird Areas within the Tana River Basin compared to refugia for birds for RCP2.6 (left) and RCP8.5 (right) (EBA GIS shapefile from Birdlife International, 2016) without dispersal

6.4.3 Species Richness

This section presents the basin-average proportion of the current species in the database remaining under future climate conditions for the 5 taxa.

6.4.3.1 Mammalia

Table 6-3 shows the mean (over grid cells and GCMs) proportion of mammals remaining in the Tana River Basin for the three time periods for the four different RCPs. The proportion remaining decreases through time. The difference between the ‘no dispersal’ and ‘realistic dispersal’ scenarios increases with higher radiative forcing and further into the future.

Figure 6-15 shows the change in mammalia richness over time (which is the same data as Table 6-3). The variation between the RCPs is narrower with realistic dispersal, suggesting that allowing species to move with the climate is beneficial for preserving biodiversity. A minor increase in the species richness from the current level is shown by the 2080s for RCP6.0 and RCP8.5 if mammals are able to disperse at realistic rates. For RCP6.0, there is a 3% increase and for RCP8.5 there is a 7% increase. For RCP4.5, 100% of the current species richness remains when realistic dispersal rates are included and for RCP2.6 only 2% of the current richness is lost.

Table 6-3: Basin-average proportion of mammals remaining within the Tana River Basin, highlighting the difference between realistic and no dispersal scenarios. Data are presented as the mean across 21 alternative climate models and the mean across the study area.

MAMMALIA	Year	No dispersal	Realistic	Difference (Real-ND)
RCP2.6	2024	0.77	0.96	0.19
	2054	0.67	0.95	0.28
	2084	0.66	0.98	0.32
RCP4.5	2024	0.77	0.96	0.19
	2054	0.63	0.95	0.32
	2084	0.56	1.01	0.45
RCP6.0	2024	0.78	0.96	0.18
	2054	0.64	0.95	0.31
	2084	0.53	1.03	0.5
RCP8.5	2024	0.74	0.95	0.21
	2054	0.55	0.95	0.4
	2084	0.45	1.07	0.62

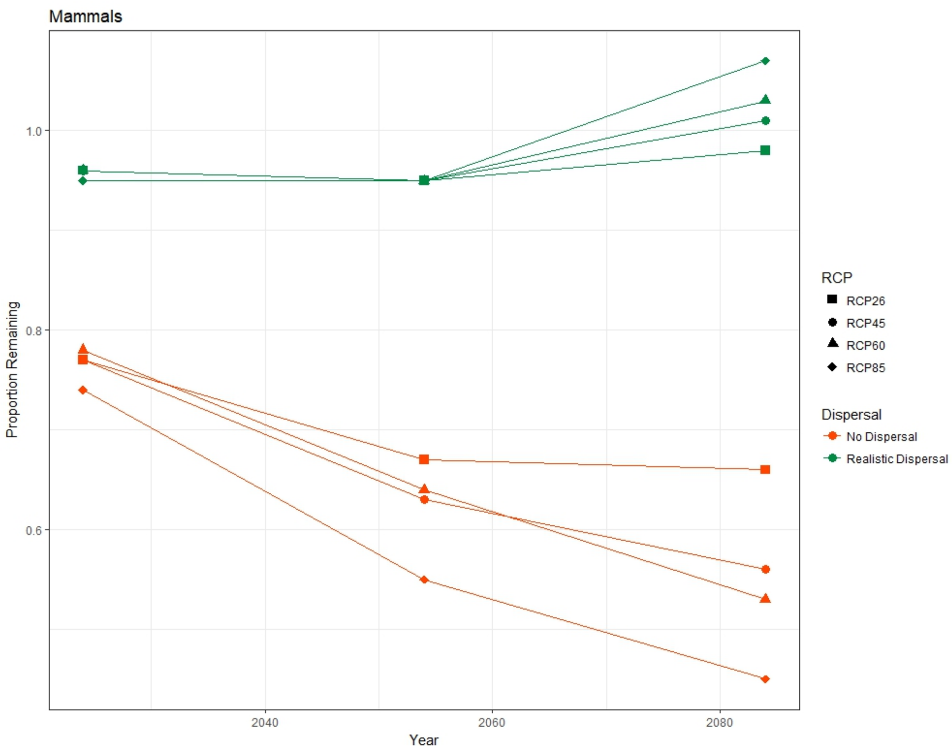

Figure 6-15: Mean proportion remaining in the basin for no dispersal (orange lines) and realistic dispersal (green lines). The different symbols represent the four RCPs. Data are presented as the mean across 21 alternative climate models and the mean across the study area.

6.4.3.2 Aves

Sizeable differences between the two dispersal scenarios exist for birds. Figure 6-16 shows the mean proportion remaining in the basin for no dispersal and realistic dispersal. In addition, Table 6-4 provides the difference between the two dispersal scenarios for the different RCPs and time periods. A low proportion of bird species are projected to remain for RCP8.5 with no dispersal. Realistic dispersal allows a greater proportion of birds to remain in the Tana River Basin. In the case of realistic dispersal, the greatest decrease is seen in the 2050s, with the proportion increasing again by the 2080s. Assuming no dispersal, this is not seen. Instead, a continued decrease further into the future is observed.

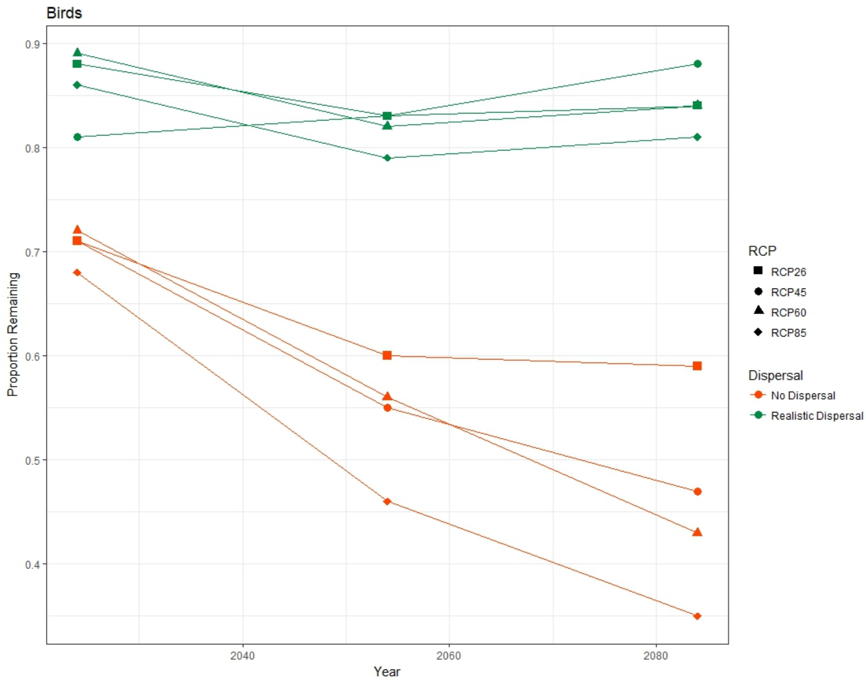

Figure 6-16: Mean proportion remaining in the basin for no dispersal (orange lines) and realistic dispersal (green lines). The symbols represent the four RCPs. Data are presented as the mean across 21 alternative climate models and the mean across the study area

Table 6-4: Basin-average proportion of birds remaining within the Tana River Basin, highlighting the difference between realistic and no dispersal scenarios. Data are presented as the mean across 21 alternative climate models and the mean across the study area.

AVES	Year	No dispersal	Realistic	Difference (Real-ND)
RCP2.6	2024	0.71	0.88	0.17
	2054	0.6	0.83	0.23
	2084	0.59	0.84	0.25
RCP4.5	2024	0.71	0.81	0.1
	2054	0.55	0.83	0.28
	2084	0.47	0.88	0.41
RCP6.0	2024	0.72	0.89	0.17
	2054	0.56	0.82	0.26
	2084	0.43	0.84	0.41
RCP8.5	2024	0.68	0.86	0.18
	2054	0.46	0.79	0.33
	2084	0.35	0.81	0.46

6.4.3.3 Reptilia

As reptiles are unlikely to disperse far in the time periods considered, only the 'no dispersal' scenario was considered here. Table 6-5 and Figure 6-17 show the proportion of species richness remaining for the different scenarios and time periods. All RCPs show a decrease in the proportion remaining further into the future. The average values show a large variation between the four different RCPs towards the end of the century (2084).

Table 6-5: Basin-average proportion of reptiles remaining within the Tana River Basin. Data are presented as the mean across 21 alternative climate models. The standard deviation (SD) is the spatial standard deviation across the basin.

Scenario		Min	Max	Mean	SD
RCP2.6	2024	0.17	1.00	0.83	0.11
	2054	0.14	1.00	0.76	0.12
	2084	0.13	1.00	0.75	0.13
RCP4.5	2024	0.17	1.00	0.83	0.10
	2054	0.08	1.00	0.72	0.13
	2084	0.07	1.00	0.67	0.14
RCP6.0	2024	0.18	1.00	0.84	0.10
	2054	0.13	1.00	0.73	0.13
	2084	0.07	1.00	0.63	0.15
RCP8.5	2024	0.13	1.00	0.81	0.11
	2054	0.07	1.00	0.65	0.14
	2084	0.08	0.90	0.52	0.14

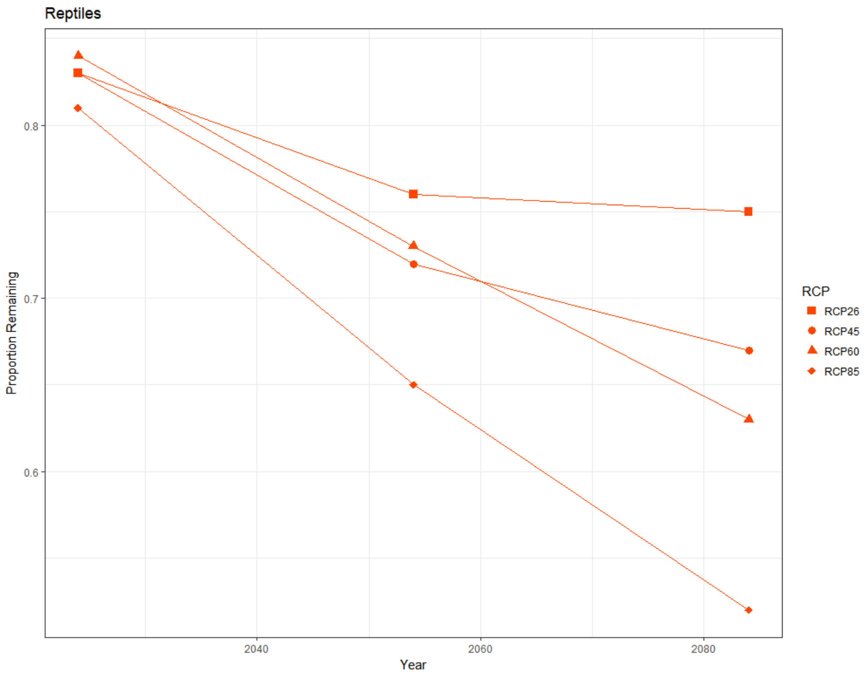

Figure 6-17: Mean proportion of reptiles remaining in the basin. Data are presented as the mean across 21 alternative climate models and the mean across the study area

6.4.3.4 Amphibia

As already seen with reptiles, Table 6-6 and Figure 6-18 show that amphibians experience decreases in species richness further into the future but mean proportions remaining do not vary greatly between the four RCPs for the 2020s, but differences become greater further into the future.

Table 6-6: Basin-average proportion of amphibians remaining within the Tana River Basin. Data are presented as the mean across 21 alternative climate models. The standard deviation (SD) is the spatial standard deviation across the basin.

	Year	**Min**	**Max**	**Mean**	**SD**
RCP2.6	2024	0.38	1.00	0.80	0.14
	2054	0.24	1.00	0.72	0.17
	2084	0.23	1.00	0.71	0.17
RCP4.5	2024	0.38	1.00	0.80	0.14
	2054	0.21	1.00	0.68	0.19
	2084	0.15	1.00	0.62	0.21
RCP6.0	2024	0.38	1.00	0.80	0.13
	2054	0.22	1.00	0.69	0.18
	2084	0.14	1.00	0.58	0.22
RCP8.5	2024	0.35	1.00	0.78	0.15
	2054	0.15	1.00	0.61	0.21
	2084	0.09	0.96	0.48	0.23

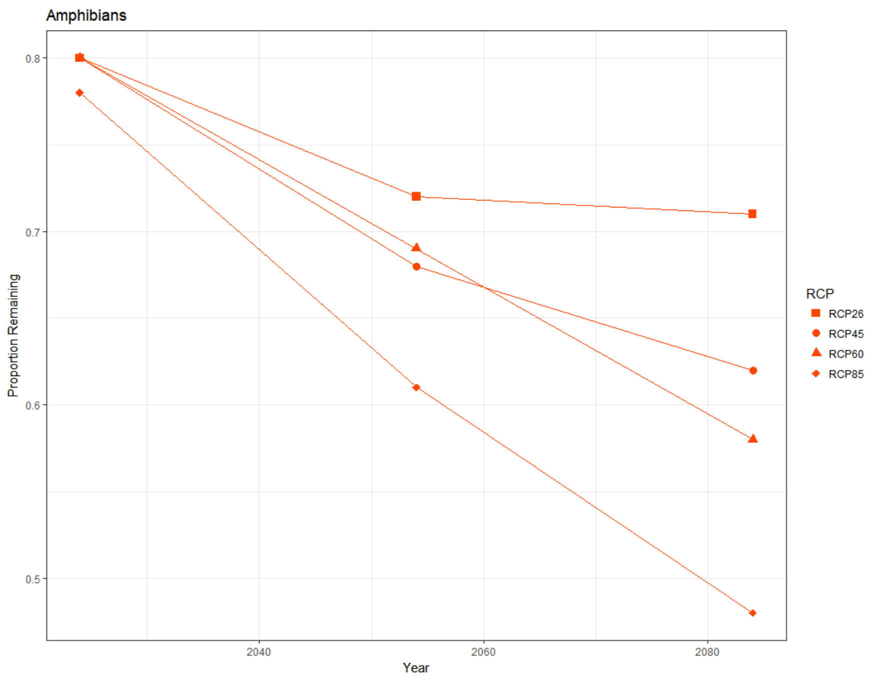

Figure 6-18: Mean proportion of amphibians remaining in the basin. Data are presented as the mean across 21 alternative climate models and the mean across the study area

6.4.3.5 Plantae

Table 6-7 and Figure 6-19 show significant reductions in the proportion of plants remaining for each RCP towards the end of the century. Under the high-end climate scenario (RCP8.5), by the 2080s the basin-average species richness is less than half that of the current.

Table 6-7: Basin-average proportion of plants remaining. Data are presented as the mean across 21 alternative climate models. The standard deviation (SD) is the spatial standard deviation across the basin.

	Year	**Min**	**Max**	**Mean**	**SD**
RCP2.6	2024	0.66	0.95	0.82	0.05
	2054	0.56	0.93	0.74	0.07
	2084	0.53	0.92	0.73	0.07
RCP4.5	2024	0.66	0.95	0.82	0.05
	2054	0.49	0.91	0.69	0.08
	2084	0.42	0.88	0.62	0.09
RCP6.0	2024	0.65	0.95	0.82	0.05
	2054	0.52	0.92	0.71	0.07
	2084	0.36	0.86	0.57	0.11
RCP8.5	2024	0.63	0.95	0.80	0.05
	2054	0.42	0.88	0.62	0.09
	2084	0.26	0.83	0.47	0.11

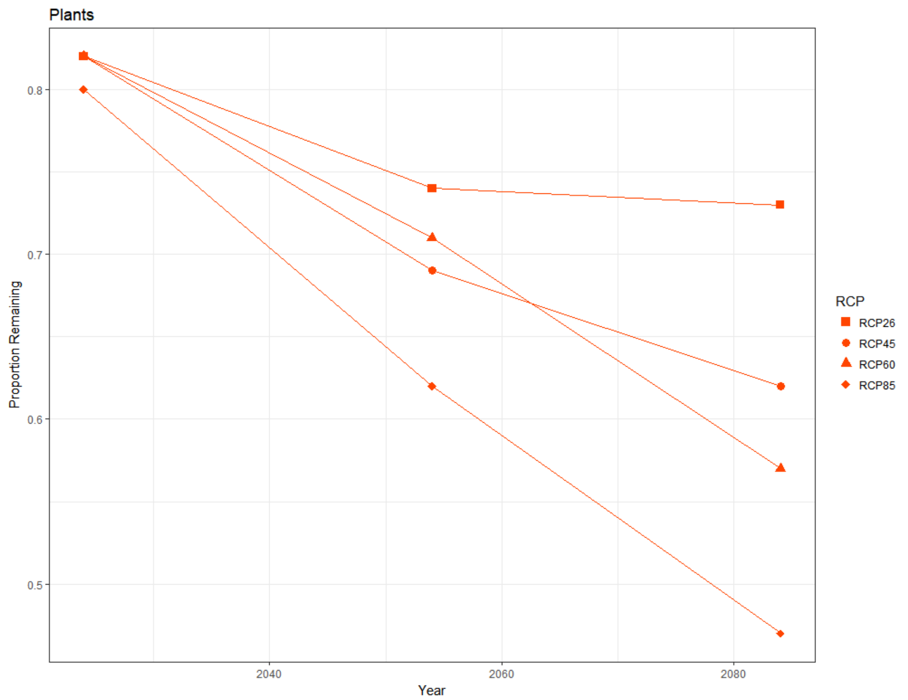

Figure 6-19: Mean proportion of plants remaining in the basin. Data are presented as the mean across 21 alternative climate models and the mean across the study area

6.4.3.6 All Taxa

A comparison between the different taxa, for the no dispersal scenarios, is provided in Figure 6-20. Most taxa are seen to be very sensitive to changes in climate, showing large losses throughout the century. By the 2080s, the variation between the different scenarios is much larger than the spread seen for the 2020s. In all cases, a greater reduction in species richness occurs with higher levels of radiative forcing.

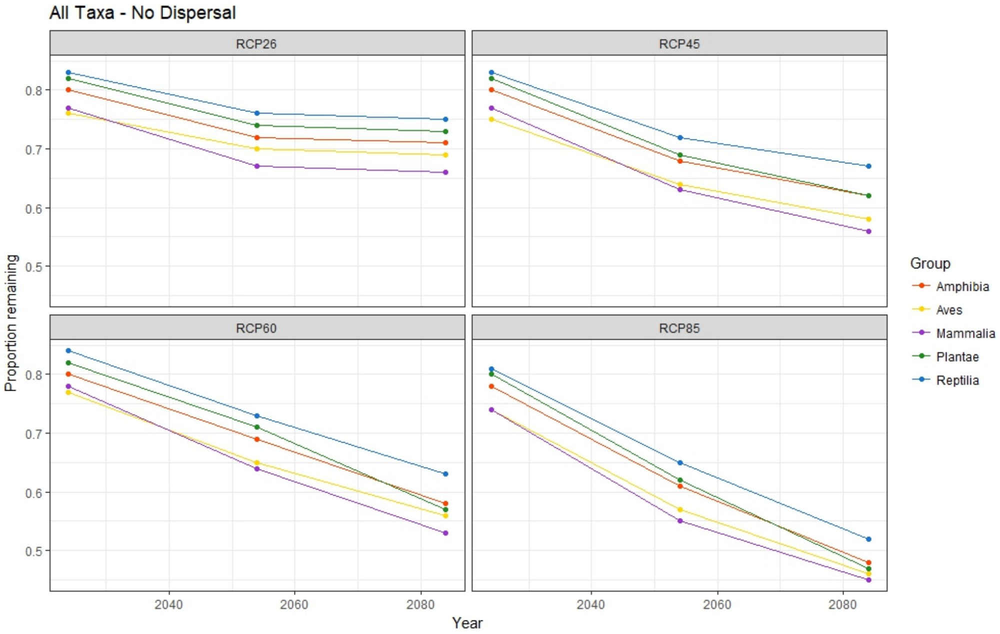

Figure 6-20: Proportion of current species richness remaining assuming no dispersal, split by RCP. Data are presented as the mean across 21 alternative climate models and the mean across the study area.

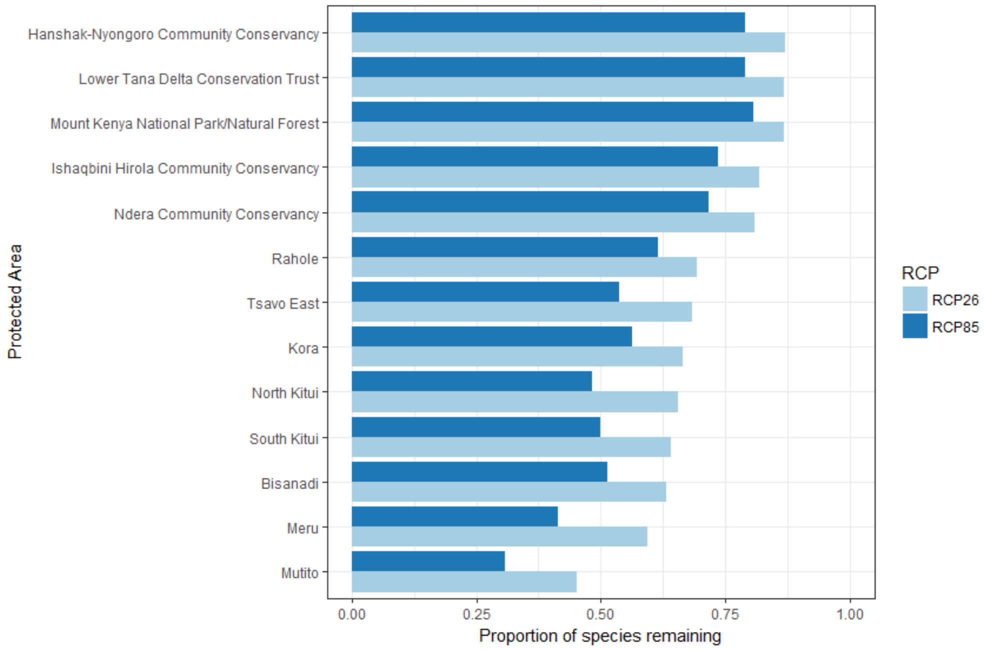

Figure 6-21: Average proportion of species remaining (across taxa) for each PA for RCP2.6 (light blue) and RCP8.5 (darker blue) for the 2050s. These results are for the no dispersal scenario. Data are presented as the mean across 21 alternative climate models.

Figure 6-21 compares the PA-average proportion of species remaining across the taxa for PAs for RCPs 2.6 and 8.5 in the 2050s, without dispersal. In all cases, a greater proportion of species remain under RCP2.6 conditions than RCP8.5. This demonstrates the importance of mitigation for biodiversity conservation.

Figure 6-22 compares the PA-average proportion of mammals and birds remaining with the two dispersal scenarios for RCP2.6 and RCP8.5. In all cases, a greater proportion of species remain when realistic dispersal is allowed. Some PAs, such as Rahole and Kora, may see an increase in species richness if animals are able to disperse under RCP8.5 conditions.

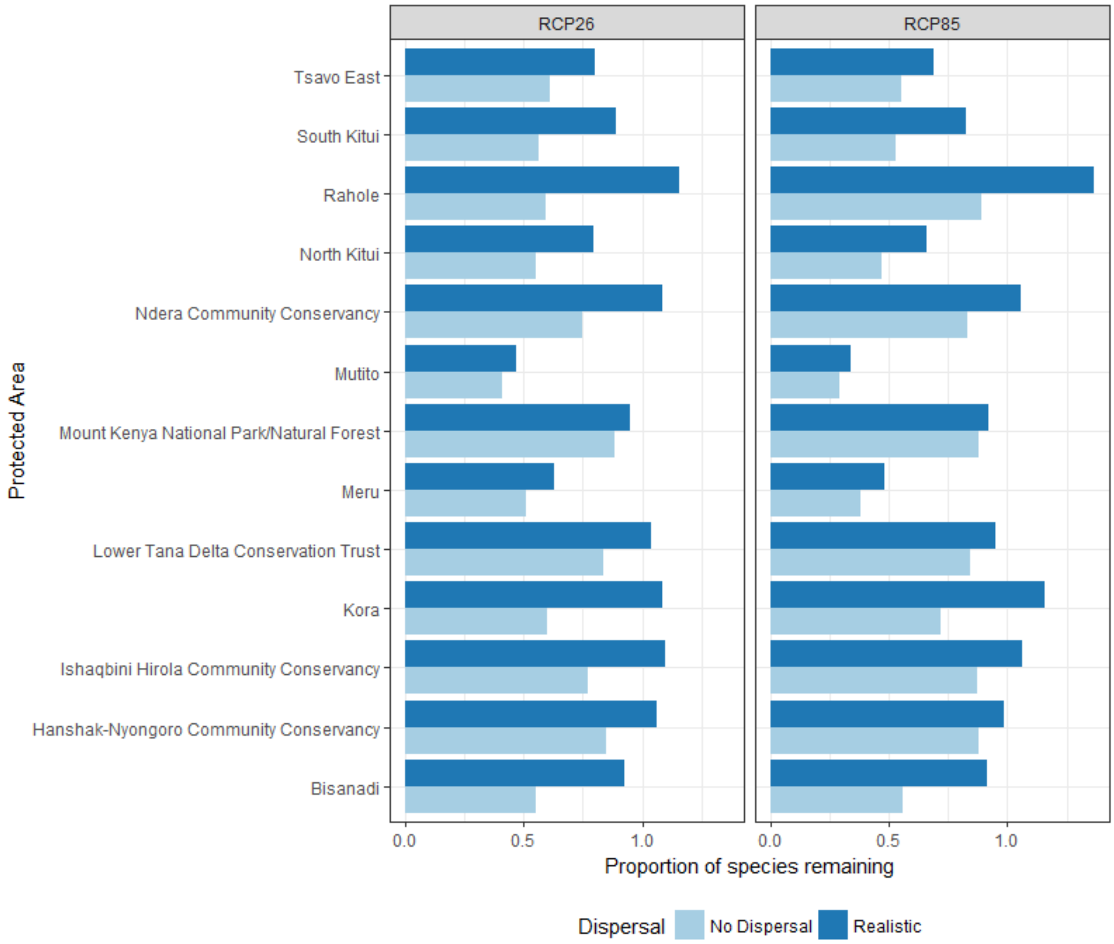

Figure 6-22: Average proportion of birds and mammals remaining for each PA for the 2050s. No dispersal is shown in light blue and realistic dispersal is shown in dark blue. Data are presented as the mean across 21 alternative climate models.

6.5 Case Study Species Results

This section will present the results of the individual case study species identified through the literature review and IUCN Red List (as described in Section 6.3.3.1). These species are a range of birds, mammals, amphibians, reptiles and plants.

Some of these species are already largely confined to PAs, including the African Buffalo, so changes in the area suitable for these species was compared to the PA network as well (Section 6.5.6). In addition to these results, a list of the case study species projected to be the most vulnerable can be found in Appendix V.

6.5.1 Current Distributions

First it is important to understand where these species occur in the basin under current conditions. Figure 6-23 shows the number of these animal species projected to be present by the model for each cell under current climate conditions. 65 animals have been analysed and the maximum number in a cell is 51, while the minimum number in a particular cell is 1 species. As shown with the taxa level results, a large number of species are found in the south of the basin close to the Tana Delta region. Unlike the taxa level results, fewer case study species occur in the highlands in the north of the basin. The lowest number of species per cell are seen in the northeast of the basin along the main river. Similar to the taxa level distributions, there is a high concentration of case study species in the south of the basin.

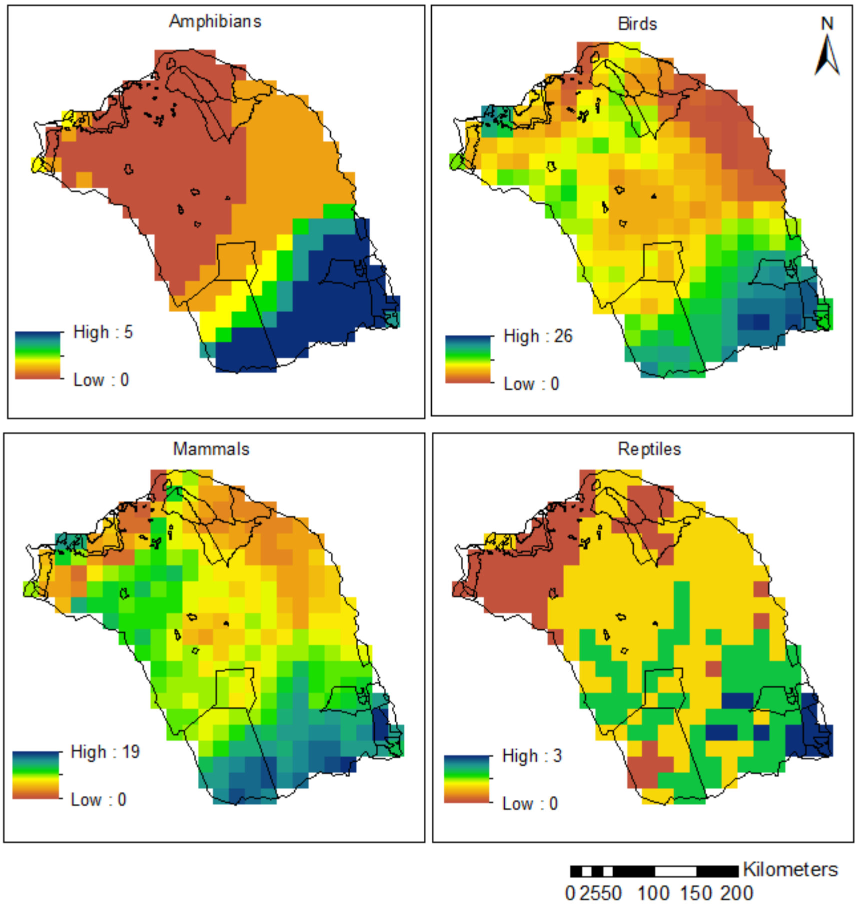

Figure 6-23: Number of individual animal species selected for the case study in each cell under current climate conditions. Black outlines show the current protected areas.

Table 6-8 briefly describes the current distribution of each animal included in the case study.

Table 6-8: Brief description of the current spatial distribution of suitability for the animals within the basin

Species	**Current Suitable Area**
Acinonyx jubatus	Majority of the basin, other than the land along the main river
Acrocephalus griseldis	Southern half of the basin
Actophilornis africanus	Suitable area near to the coast and in the mountains
Afrixalus delicatus	Large band of suitable land closest to the coast
Anthreptes reichenowi	South eastern basin and some in the mountains
Aonyx capensis	In the northern uplands and along coast
Aquila nipalensis	Patchy distribution in the west of the basin
Ardea alba	Southern and in the mountains
Ardeola idae	Western and southern basin
Arenaria interpres	South eastern basin
Atilax paludinosus	Widespread across the floodplain
Balearica pavonina	Majority of the basin, other than the land along the main river in the north
Balearica regulorum	Western half of basin
Calidris alba	South eastern basin
Cercopithecus albogularis	Band of suitable land closest to the coast
Ceryle rudis	Largely suitable, apart from the very north
Charadrius asiaticus	South eastern basin
Charadrius mongolus	Delta
Chelonia mydas	Eastern half of the basin
Circaetus fasciolatus	Band of suitable land closest to the coast
Circus macrourus	Patchy distribution in the north of the basin
Circus pygargus	North of the basin but not the mountains
Damaliscus lunatus	Small area of suitable land in the west
Dasypeltis scabra	South eastern around the delta
Dicrurus modestus	Southern and in the mountains
Eidolon helvum	South eastern basin and some in the mountains
Eretmochelys imbricata	Patchy distribution in southern basin
Erythrocebus patas	Patchy distribution around the south
Falco chicquera	Central basin and Tana delta region
Giraffa camelopardalis	Majority of the basin, other than the land along the main river
Gyps africanus	Limited number of cells, mainly in the southwest
Hippopotamus amphibius	Majority of the basin
Hipposideros vittatus	Western basin, not in the mountains
Hydrictis maculicollis	South eastern basin but not nearest the coast
Hyperolius argus	Southern basin
Hyperolius tuberilinguis	Southern basin
Kobus kob	South eastern basin
Leptailurus serval	Band of suitable land closest to the coast
Leptopelis flavomaculatus	Sothern basin
Litocranius walleri	Majority of the basin
Loxodonta Africana	Limited to the west of the basin. There are some small patches of suitable land in the upland region.
Lycaon pictus	Across the floodplain and in some upland areas.

Table 6-8

Necrosyrtes monachus	Majority of the basin, other than the land along the main river in the north
Nettapus auritus	Suitable land in the Tana delta region
Otomops martiensseni	Majority of the basin
Ourebia ourebi	Southern and western basin
Panthera leo	Suitable area in the west of the basin
Panthera pardus	West, south and central basin suitable
Pelecanus rufescens	Southern and central basin
Phoeniconaias minor	South eastern basin and some in the mountains
Phoeniculus damarensis	North of the basin but not the mountains
Podica senegalensis	Limited to a band of land closest to the coast.
Pyxicephalus edulis	Southern half of the basin
Rynchops flavirostris	Limited distribution across central basin and in delta
Sheppardia gunningi	Southern and in the mountains
Stephanoaetus coronatus	Southern and in the mountains
Struthio camelus	Western half of the basin is suitable
Syncerus caffer	West of the basin and in a band near the coastal zone.
Tauraco fischeri	South eastern basin
Torgos tracheliotus	Patchy distribution across majority of the basin, other than the land along the main river in the north
Tragelaphus imberbis	Majority of the basin other than the mountains in the northwest
Trigonoceps occipitalis	Southern basin and some in the mountains
Tringa stagnatilis	Patchy distribution in the south and west of the basin
Trionyx triunguis	Central basin
Xenus cinereus	South eastern basin

Figure 6-24 shows the number of the 31 plant species present for each cell under current climate conditions. The majority of species are found in the south of the basin, suggesting that these species are more suited to areas of lower elevation and rainfall. The highest number of plants in a single cell is 29.

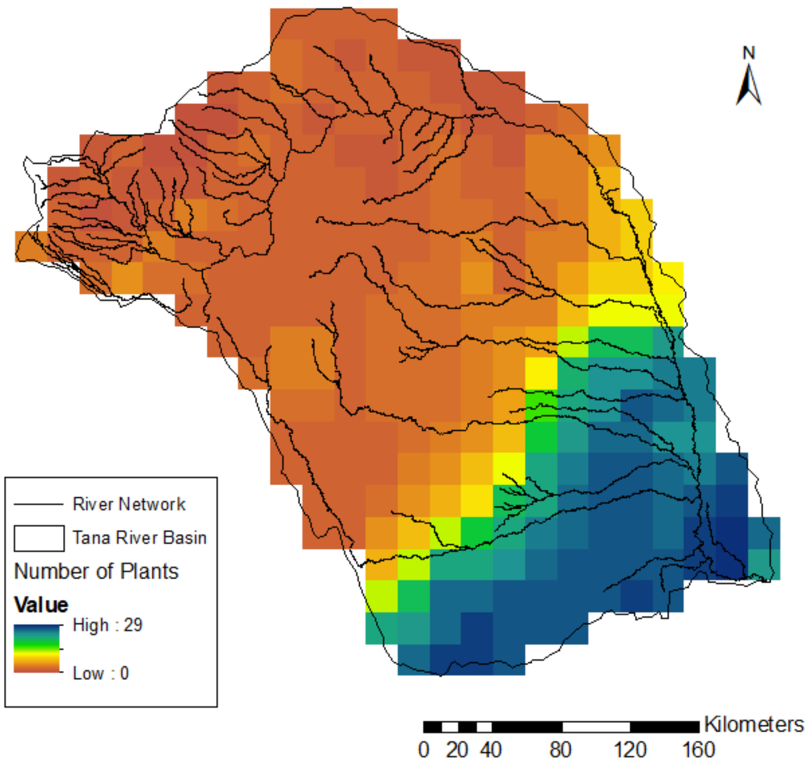

Figure 6-24: Number of individual plant species selected for the case study in each cell within the Tana River Basin under current conditions. The black lines show the river network.

6.5.2 Changes to Areas Suitable for Mammals

22 mammals have been analysed. In Figures 6-25 and 6-26, the mammals have been split according to their IUCN Red List status. Figure 6-25 shows the changes to the number of suitable cells without dispersal. The African wild dog (*Lycaon pictus*) is the only endangered (EN) category mammal. Relatively few cells are suitable under current climate conditions. Without dispersal, the number of cells suitable for this species reduces to 0 with 4.5°C of warming.

The number of suitable cells for all vulnerable (VU) mammals decreases with higher temperatures. The giraffe (*Giraffa camelopardis*) and hippo (*Hippopotamus amphibius*) appear to be particularly sensitive, with large reductions in the number of suitable cells seen for all levels of warming. Substantial reductions are seen with the cheetah (*Acinonyx jubatus*) and leopard (*Panthera pardus*) with higher temperatures. There are fewer suitable cells for lion (*Panthera leo*) under current conditions. Of the NT mammals, the Giant Mastiff Bat (*Otomops martiensseni*) and lesser kudu (*Tragelaphus imberbis*) are the most sensitive to high temperature increases. The gerenuk (*Litocranius walleri*) has a particularly large suitable climate space under current conditions. Reductions in the area suitable for this species are relatively small.

Minimal changes are seen for some LC species, including the Sykes' Monkey (*Cercopithecus mitus*), marsh mongoose (*Atilax paludinosus*) and serval (*Leptailurus serval*). Contrastingly, with 4.5°C of warming, there are no suitable cells for topi (*Damaliscus lunatus*). The African buffalo (*Syncerus caffer*) shows a reduction in the number of suitable cells with 1.5°C of warming, but changes to the number of suitable areas are not substantial with higher temperatures. Generally, the reduction in EN and VU species are greater than the NT and LC category mammals.

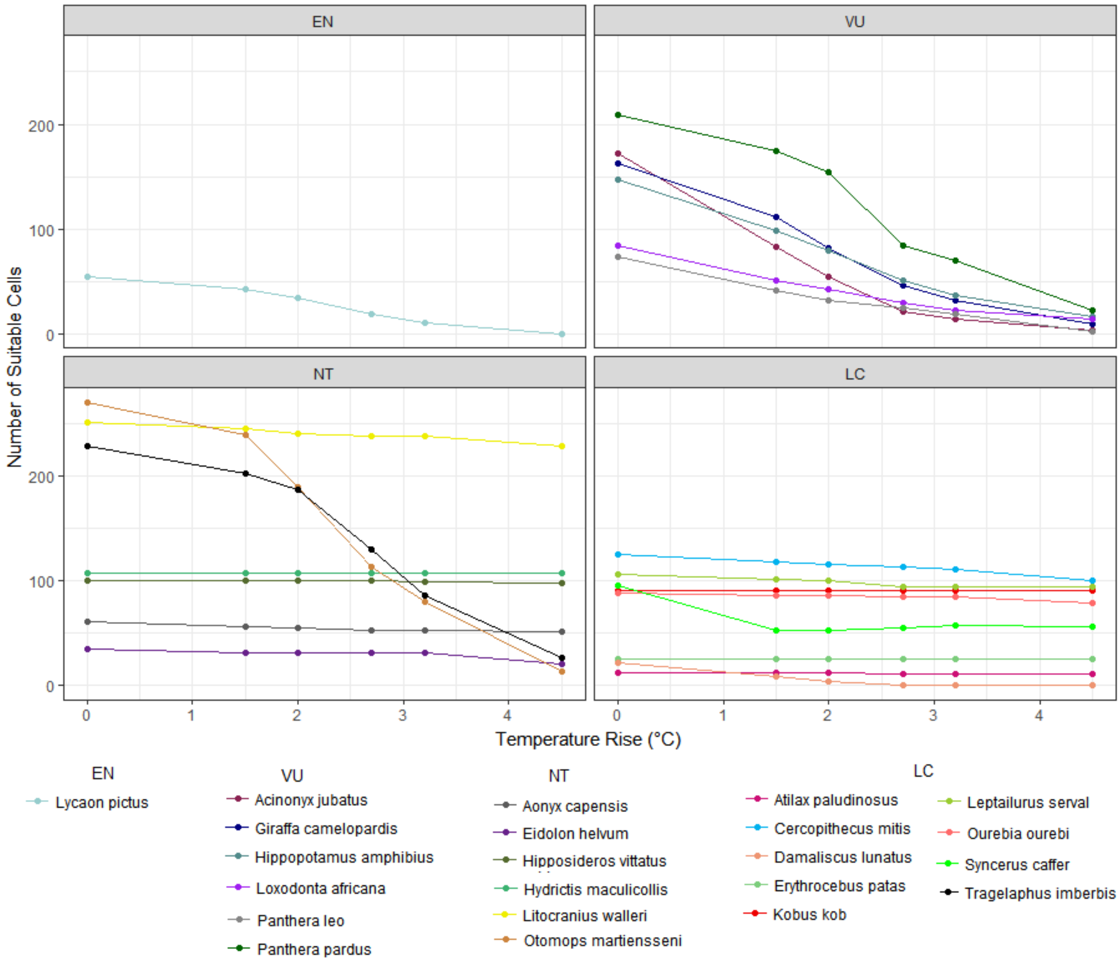

Figure 6-25: Number of cells suitable for the case study mammals with no dispersal. The species are split by IUCN Red List status. Data are presented as the mean across 21 alternative climate models.

Figure 6-26 shows the changes to suitable areas for mammals, with realistic dispersal. The importance of dispersal is shown to be particularly important for the NT and LC species. Many of these species see increases in the suitable climate space within the basin if dispersal is allowed. Increases in the number of suitable cells are seen for Patas monkey (*Erythrocebus patas),* marsh mongoose *(Atilax paludinosus),* straw-coloured fruit bat *(Eidolon helvum),* African clawless otter *(Aonyx capensis),* Striped leaf-nosed bat *(Hipposideros vittatus),* kob *(Kobus kob),* oribi *(Ourebia ourebi),* serval *(Leptailurus serval)* and Spotted-necked otter *(Hydrictis maculicollis).* By contrast, the EN and VU mammals still see substantial reductions in the number of suitable cells when dispersal is included.

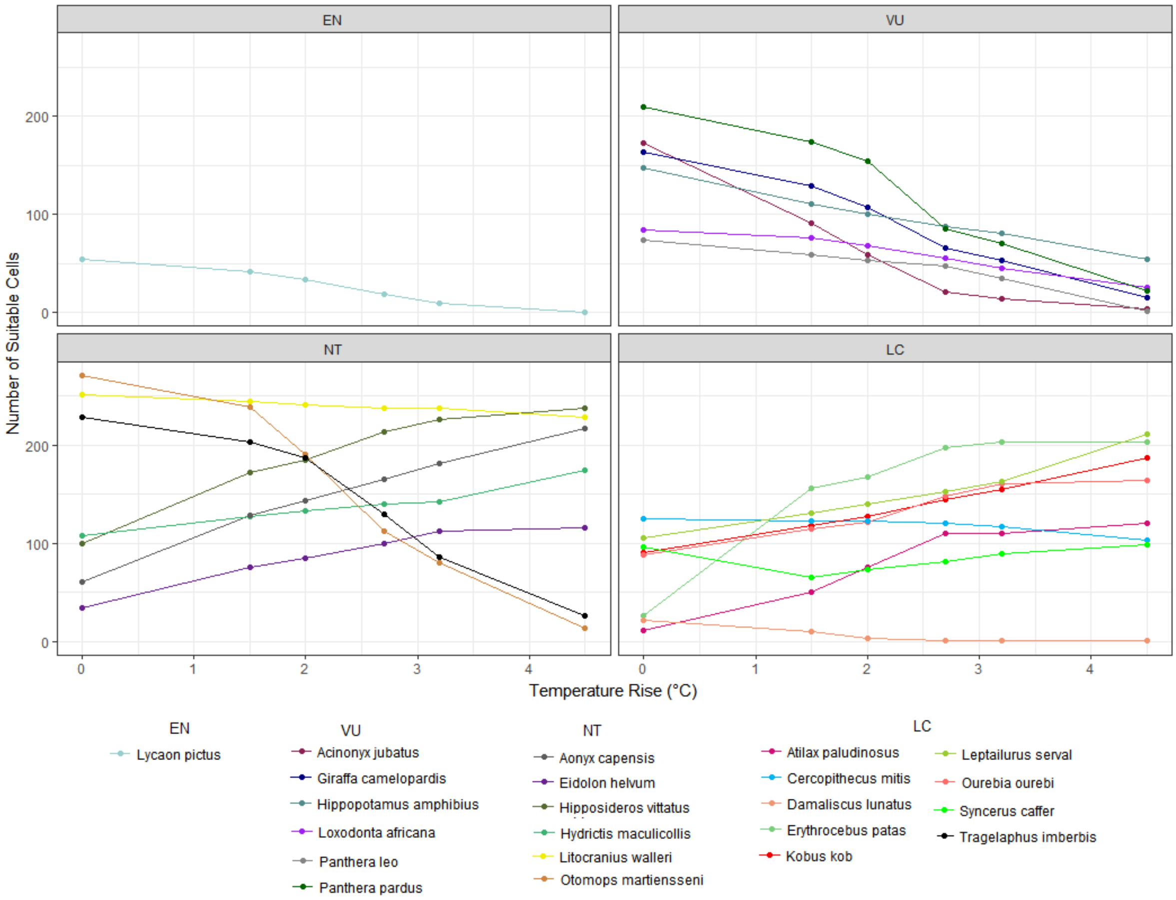

Figure 6-26: Number of cells suitable for the case study mammals with realistic dispersal. The species are split by IUCN Red List status. Data are presented as the mean across 21 alternative climate models.

6.5.3 Changes to Areas Suitable for Birds

Figures 6-27 and 6-28 show the number of cells suitable for the chosen birds, with no dispersal. The birds which are classified as LC on the IUCN Red List have been split further; either classified by the most significant threat (climate, agriculture or wetland degradation) or by their importance for tourism. The common ostrich is the only LC bird classed as important for tourism.

Figure 6-27 shows the CR-NT birds assuming no dispersal. All of the birds experience decreases in the areas suitable with higher temperatures. Of the three critically endangered (CR) birds, the number of cells suitable for white-backed vulture (*Gyps africanus*) and white-headed vulture (*Trigonoceps occipitalis*) reduces significantly, with no cells remaining suitable for either species with 4.5°C. A large proportion of the basin is suitable for the hooded vulture (*Necrosyrtes monachus*) under current climate conditions. Although the number of suitable cells reduces with higher temperatures, the proportion of the suitable area lost is smaller than the other CR species.

No cells remain suitable for the lappet-faced vulture (*Torgos tracheliotus*), steppe eagle (*Aquila nipalensis*) or Basra reed warbler (*Acrocephalus griseldis*) with warming of 4.5°C. Significant reductions in the suitable climate space are also shown for the other two EN birds: the Malagasy pond heron (*Ardeola idea*) and grey crowned crane (*Balearica regulorum*). The black crowned crane (*Balearica pavonina*) is the only vulnerable (VU) bird species included in this analysis. Reductions in suitable climate space with higher temperatures are not marked. Of the near threatened (NT) birds, the red-necked falcon (*Falco chicquera*) shows the greatest sensitivity to warming. The number of cells suitable for the lesser flamingo *(Phoeniconaias minor)* reduces with temperature rises of up to 2.7°C but then increase again with higher temperatures.

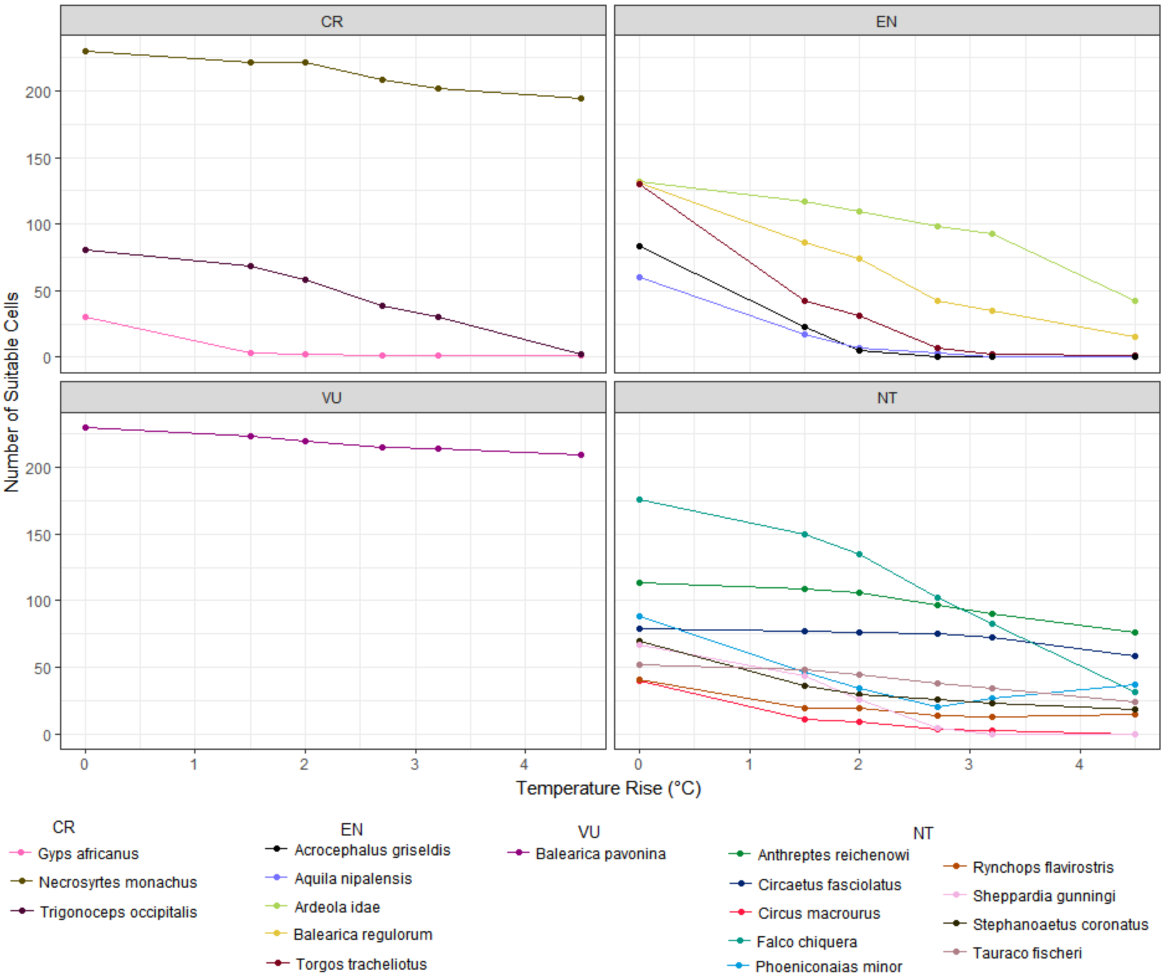

Figure 6-27: Number of cells suitable for the threatened (CR, EN, VU) or near threatened (NT) case study birds with no dispersal. The species are split by IUCN Red List status. Data are presented as the mean across 21 alternative climate models.

Figure 6-28 splits the least concern (LC) birds into the reason behind including them in this analysis. Climate, agriculture and wetland degradation are specific threats to the species, as listed on the IUCN Red List website, whereas the ostrich was included as it is an iconic tourist species. Reductions in the area suitable are seen for the majority of these species. One exception is the pink-backed pelican (*Pelecanus rufescens)*, which decreases up to 3.2°C of warming but then increases again by 4.5°C. The pied kingfisher (*Ceryle rudis)* is particularly sensitive to climate changes. Some LC birds, such as the African finfoot (*Podica senegalensis)* and African pygmy goose (*Nettapus auritus)* have a very low number of suitable cells under current climate conditions. The changes to the suitable climate space with warming are minor.

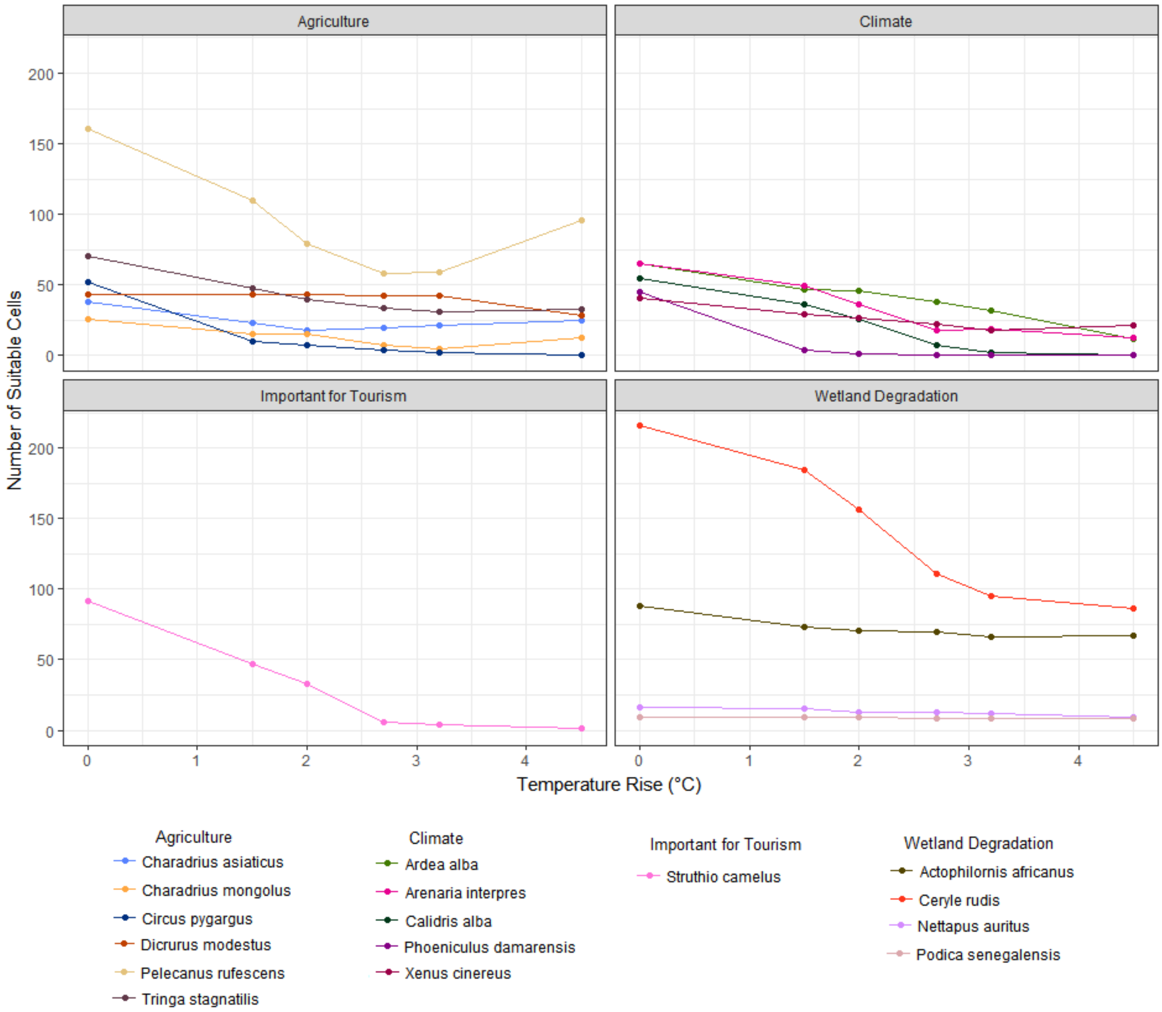

Figure 6-28: Number of suitable cells for LC case study birds. The species are split by threat or importance. Data are presented as the mean across 21 alternative climate models.

With realistic dispersal, the number of cells suitable for some birds increases with higher temperatures, as shown in Figure 6-29 for the CR-NT birds. G*yps africanus* and *Trigonoceps occipitalis* are not significantly affected by the ability to disperse.

The proportion of the basin suitable for *Necrosyrtes monachus* increases with realistic dispersal up to 2°C of temperature rise, but then reduces again with further warming.

There is no significant difference between the two dispersal scenarios for the EN birds. As seen with no dispersal, no cells remain suitable for *Torgos tracheliotus*, *Aquila nipalensis* or *Acrocephalus griseldis* with warming of 4.5°C. By contrast, *Balearica pavonina* sees an increase in suitable climate space with higher temperatures when dispersal is allowed. Of the near threatened (NT) birds, the number of cells suitable for the African skimmer (*Rynchops flavirostris*) increases significantly with higher temperatures when realistic dispersal is included.

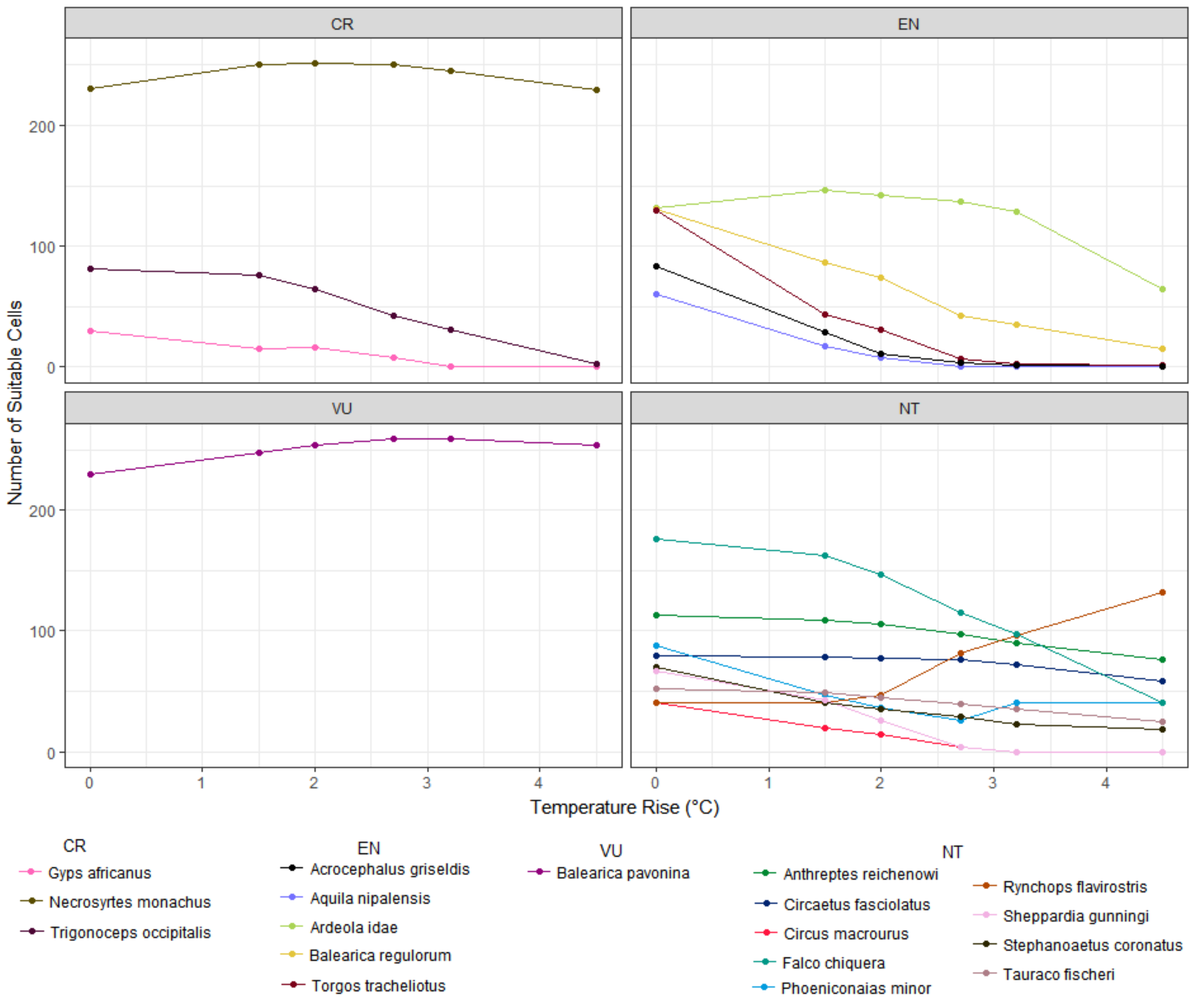

Figure 6-29: Number of cells suitable for the threatened (CR, EN. VU) or near threatened (NT) case study birds with realistic dispersal. The species are split by IUCN Red List status. Data are presented as the mean across 21 alternative climate models.

Figure 6-30 shows the changes to the number of suitable cells for the least concern bird species, when realistic dispersal rates are included. The most notable differences between realistic dispersal and the no dispersal scenario shown in Figure 5-28 are the changes to the African pygmy goose (*Nettapus auritus)* and

African jacana (*Actophilornis africanus)*, both of which are also threatened by wetland degradation. With realistic dispersal, the number of cells suitable for these birds increases with higher temperatures.

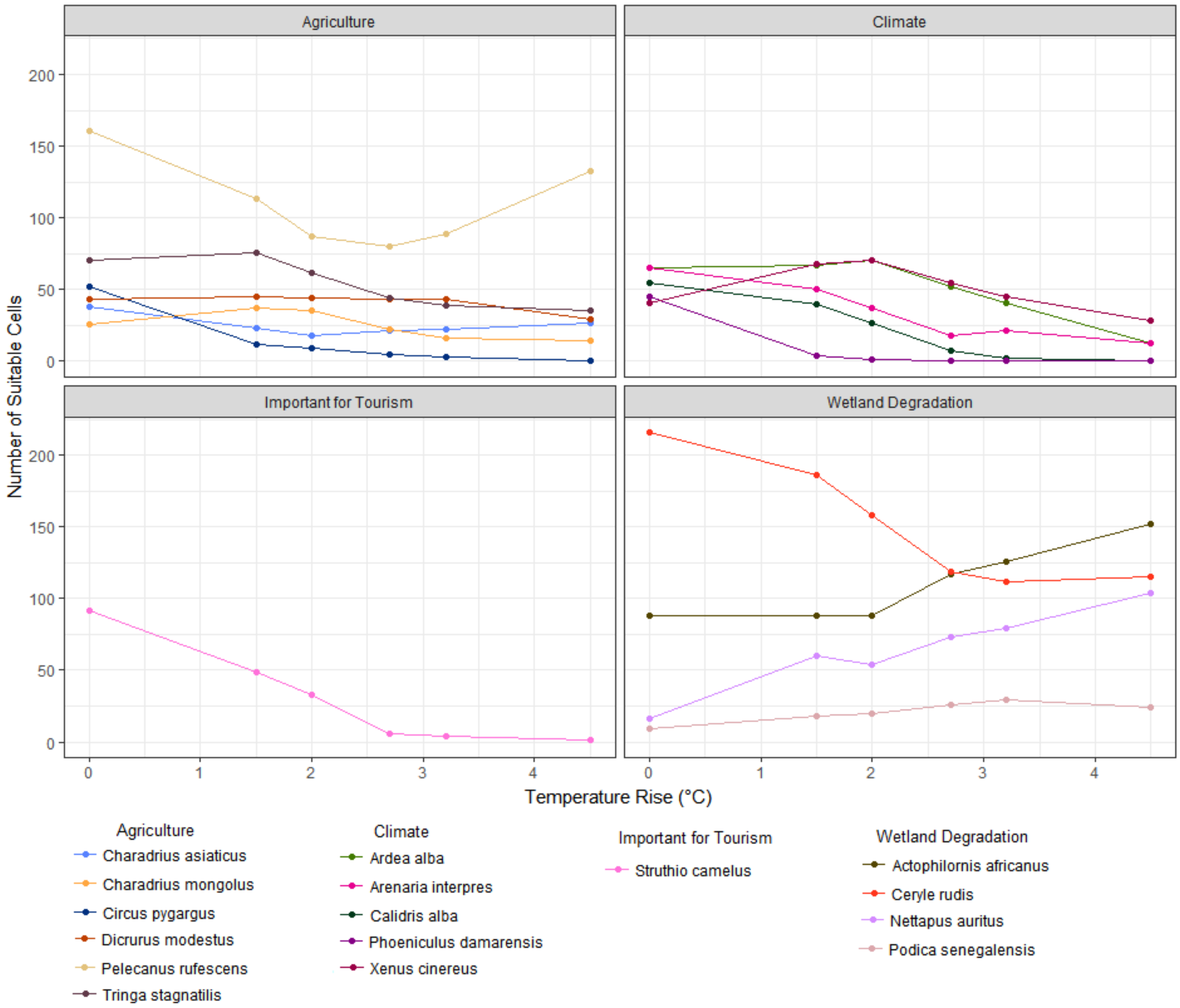

Figure 6-30: Number of suitable cells for LC case study birds with realistic dispersal. The birds are split into categories based on their importance or known threats to the species. Data are presented as the mean across 21 alternative climate models.

A full list of case study mammals and bird species with increasing climate suitability within the basin when realistic dispersal rates are considered is provided in Appendix V.

6.5.4 Changes to Areas Suitable for Selected Plants

Figure 6-31 shows the IUCN Red List plants. This does not include the five species of plants that are food sources for the critically endangered primates. These species are presented separately in Figure 6-32.

With 4.5°C warning, no cells remain suitable for *Saintpaulia ionantha, Psydrax faulknerae, Pteleopsis tetraptera, Brachylaena huillensis, Cynometra webberi* or *Gardenia transvenulosa*. In addition, *Dalbergia bracteolata* is sensitive to climate change. Many of the VU plants do not experience significant reductions in the number of suitable cells with higher temperatures. This contrasts with the taxa level analysis for plants, which projected large decreases over time, suggesting that these case study species are not representative of the majority of plants in the basin.

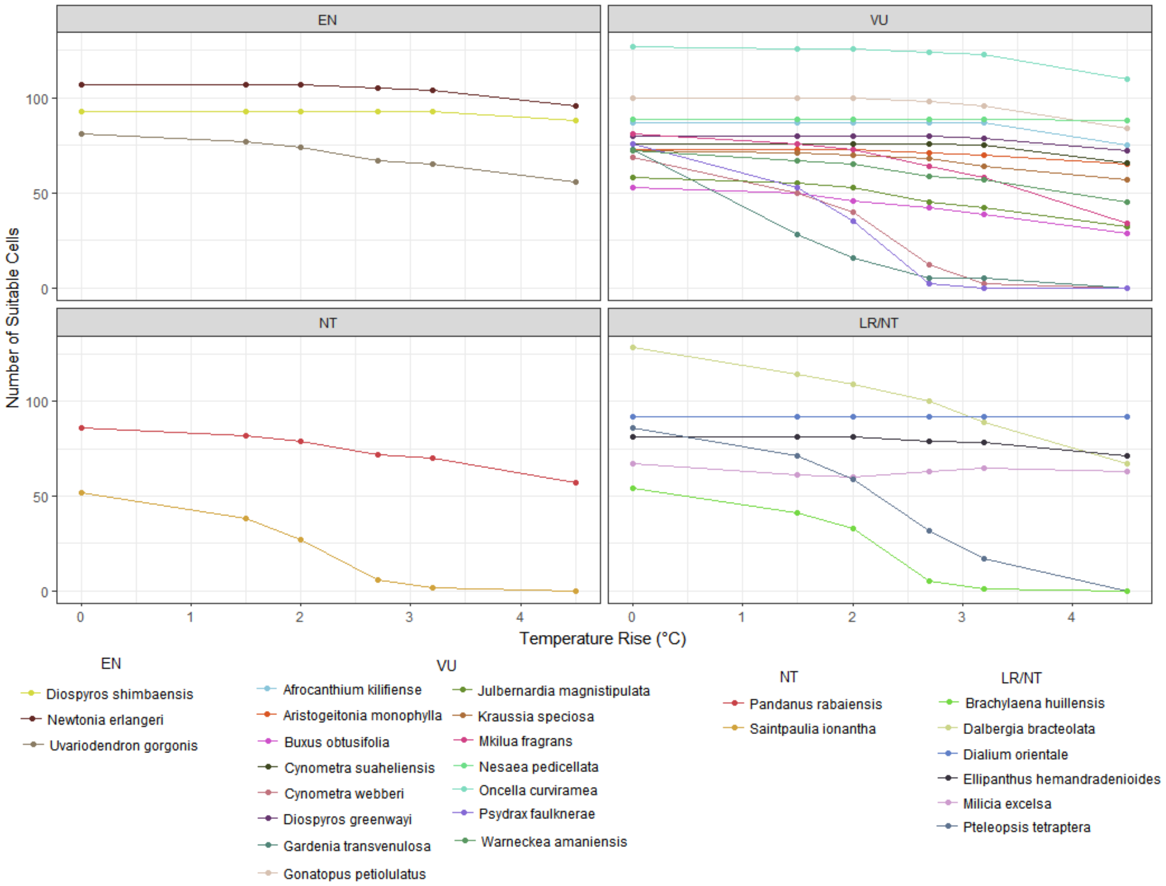

Figure 6-31: Number of suitable cells for case study plants with different levels of warming. Plants are split into categories based on their IUCN Red List status (EN, VU, NT and LR/NT). Data are presented as the mean across 21 alternative climate models.

Similarly, Figure 6-32 shows that the changes to the number of cells suitable for the five plant species used as food sources by the endangered primates (as noted by Wieczkowski and Kinnaird (2008)) is minimal with higher temperatures.

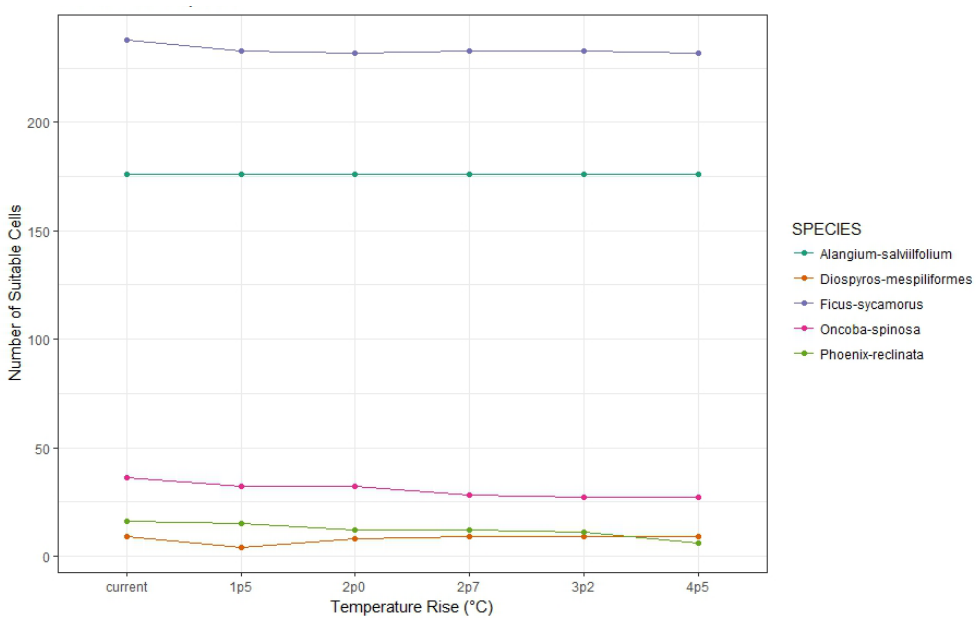

Figure 6-32: Number of cells suitable for each of the five plants that provide food for the endangered primates (as described by Wieczkowski and Kinnaird (2008)) with different levels of warming. Data are presented as the mean across 21 alternative climate models.

6.5.5 Changes to Areas Suitable for Amphibians and Reptiles

Five amphibians and four reptiles were considered in the case study. Figure 6-33 shows the number of cells where these species are present. The reptiles *Chelonia mydas* and *Trionyx triunguis* are particularly sensitive to climate change. There is a particularly high number of suitable cells for the amphibian *Pyxicephalus edulis* under current climate conditions. This species does not appear to be sensitive to higher temperatures, as no change in the number of suitable cells occurs. Similarly, the number of cells climatically suitable for *Dasypeltis scabra* does not change significantly.

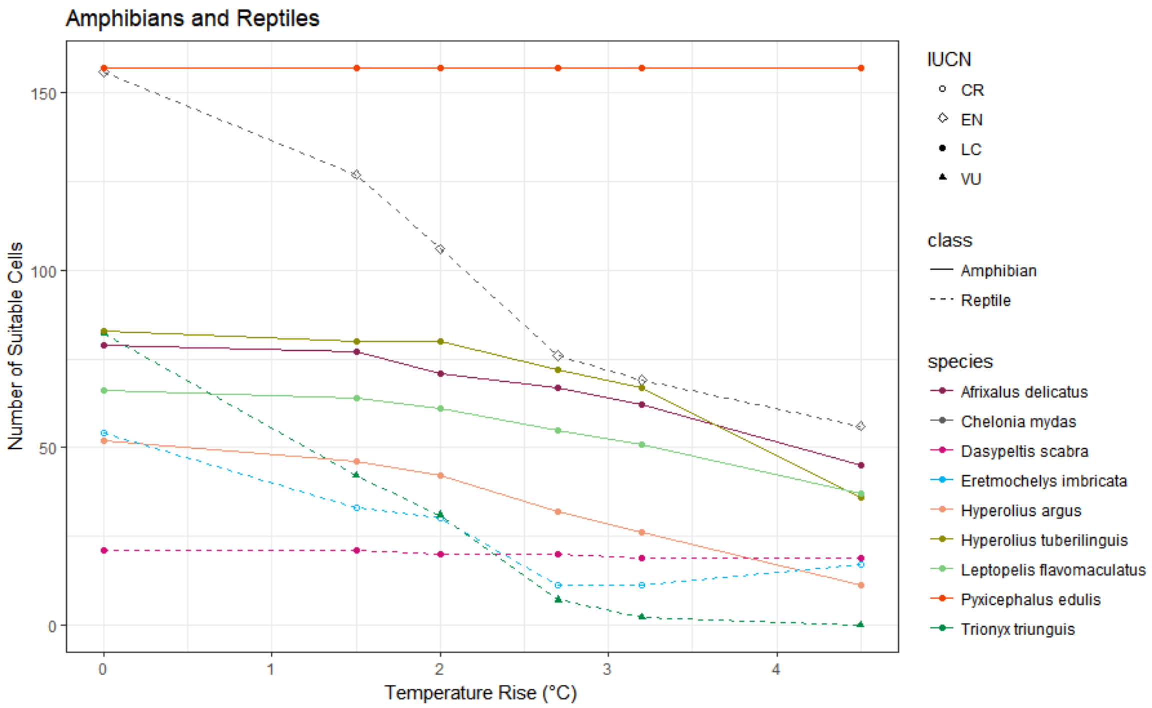

Figure 6-33: Number of cells suitable for the case study amphibians (solid lines) and reptiles (dashed lines) with different levels of warming. The symbols show the IUCN Red List status of each species. Data are presented as the mean across 21 alternative climate models.

6.5.6 Comparison with Protected Areas

This section compares the chosen species to the PAs to quantify the extent to which this network protects the case study species and plants and animals with changes to climate by taxon. Due to the low numbers analysed, for this section reptiles and amphibians have been presented on the same figure.

6.5.6.1 Mammals

22 mammals were identified and considered in this analysis. There are no PAs in the basin that are suitable for all of the mammals under current climate conditions. Figure 6-34 shows the number of mammals that each PA is climatically suitable for under current conditions and in the future, with and without dispersal. Tsavo East and Hanshak-Nyongoro Community Conservancy are suitable for the largest number of mammals for current conditions. Both of these PAs are located in the south of the basin. Few PAs are suitable for the same number of these mammals with future warming. With any level of warming above the current temperatures, Imenti or Upper Imenti becomes unsuitable for all of the mammals analysed here. Ishaqbini Hirola Community Conservancy and the Lower Tana Delta Conservation Trust (both in the south of the basin along the main Tana River) do not see large decreases in the number of mammals with higher temperatures. These two PAs

were also found to be important at the taxa level (Section 6.4.2 and Appendix III) and were projected to contain climate refugia for animals.

Figure 6-34: The number of case study mammals present in the protected areas with different levels of warming for the two dispersal scenarios (pink – no dispersal; green – realistic dispersal).

With realistic dispersal, the change in the suitability of PAs is not as clear. Generally, allowing species to move across the landscape means that the PAs remain suitable for a greater number of case study mammals. Some PAs, such as Rahole, become suitable for more mammal species with higher temperatures. Others see increases in the number of mammals under some levels of warming, but decreases for other temperatures. Examples of this are the Ishaqbini Hirola and Ndera Community Conservancies, which both become suitable for more mammals with temperature increases of up to 3.2°C, but decreases by 4.5°C of warming. There are still a number of important PAs that become unsuitable for many of the mammals even when the species are able to disperse. Of particular importance is the decrease in the number of mammals in Tsavo East National Park with higher temperatures. Under current conditions, Tsavo East is suitable for 20 out of the 22 mammals analysed. With 4.5°C of warming, this number is reduced to 12.

6.5.6.2 Birds

A similar situation is seen for the 34 birds which were included in the species of interest, as shown in Figure 6-35. The Tsavo East National Park, Ndera Community Conservancy, Lower Tana Delta Conservation Trust, Ishaqbini Hirola Community Conservancy and Hanshak-Nyongoro Community Conservancy are suitable for the largest number with current climatic conditions. There are no PAs where all 34 case study birds are present under current or future conditions. When species are not able to move with the changing climate (no dispersal), all PAs see decreases in the number of species they are suitable for as the temperature rises. Under the BAU scenario and without dispersal, Rahole National Reserve and the Imenti or Upper Imenti Forest Reserve become unsuitable for all 34 bird species.

Figure 6-35: The number of case study birds present in the protected areas with different levels of warming for the two dispersal scenarios (pink – no dispersal; green – realistic dispersal).

The majority of PAs still see decreases in the number of birds they are suitable for when dispersal is included. For many PAs, including realistic dispersal rates allows more species to remain in the PAs with each level of warming. The Ishaqbini Hirola, Hanshak-Nyongoro and Ndera Community Conservancies initially become suitable for a greater number of case study birds, but by 2.7°C of warming the number has decreased again. The Imenti or Upper Imenti Forest Reserve becomes unsuitable for all of the bird species with the highest level of warming but, by contrast, the Rahole National Reserve remains suitable for a limited number of case study birds when dispersal is considered.

6.5.6.3 Amphibians and Reptiles

A different situation can be seen for the reptiles and amphibians. Fewer species were analysed (just 9 in total), so the changes with temperature increments are not as apparent. There are no PAs that contain all 9 species under current conditions or with warming. Decreases in the numbers of amphibians and reptiles in some PAs can still be seen, as shown in Figure 6-36. The Lower Tana Delta Conservation Trust and the Hanshak-Nyongoro Community Conservancy remain suitable for the same number of these amphibians and reptiles with all levels of warming. Mutito Forest Reserve becomes unsuitable for all case study reptiles and amphibians with any increase in temperature. Meru, Bisanadi and North Kitui also become unsuitable for all nine species with higher temperatures. However, under current conditions, these four PAs were only suitable for one reptile.

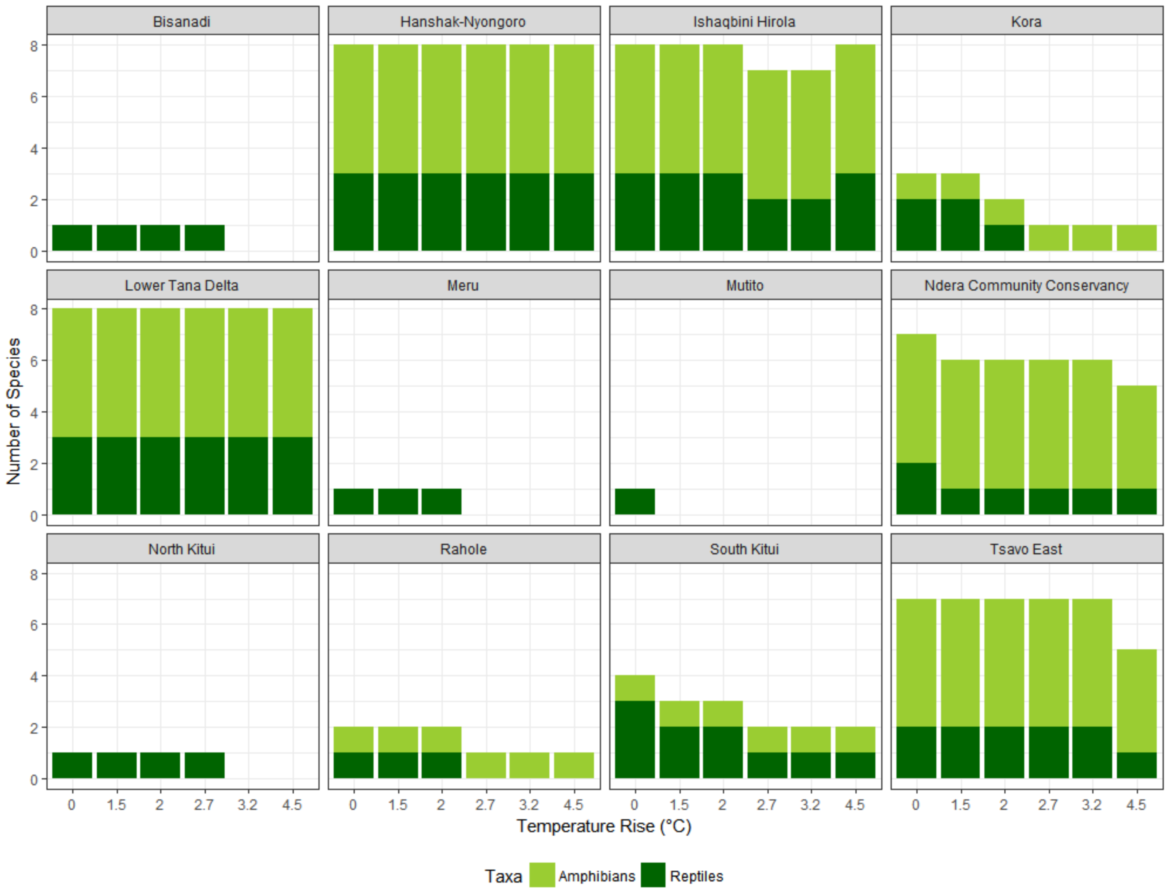

Figure 6-36: The number of case study amphibians (light green) and reptiles (dark green) present in the protected areas with different levels of warming

6.5.6.4 Plants

Under current conditions, the PAs are either home to a very large proportion of the case study plants or a very small proportion of these species, as shown in Figure 5-37. As seen with the animals, the Lower Tana Delta Conservation Trust, Tsavo East, Ndera Community Conservancy, the Ishaqbini Hirola Community Conservancy and the Hanshak-Nyongoro Community Conservancy contain the highest numbers under current climate conditions. Suitable climate space for 30 out of 31 plants is found in the Tsavo East National Park under current conditions. This number only decreases with temperature rises of over 2°C. Aberdare and Mount Kenya National Forest become unsuitable for all case study plants under the BAU scenario. These results contrast to the taxa results for plants (Section 6.4.2; Figures 6-10 and 6-11), which suggested that under the highest levels of warming, only Mount Kenya National Park would contain refugia for plants. It is likely that this difference comes from the fact that most of the plant species identified for the case study are more suited to the lower basin than the mountains (i.e. most of the species that are likely to find refugia in the mountains were not in the case study).

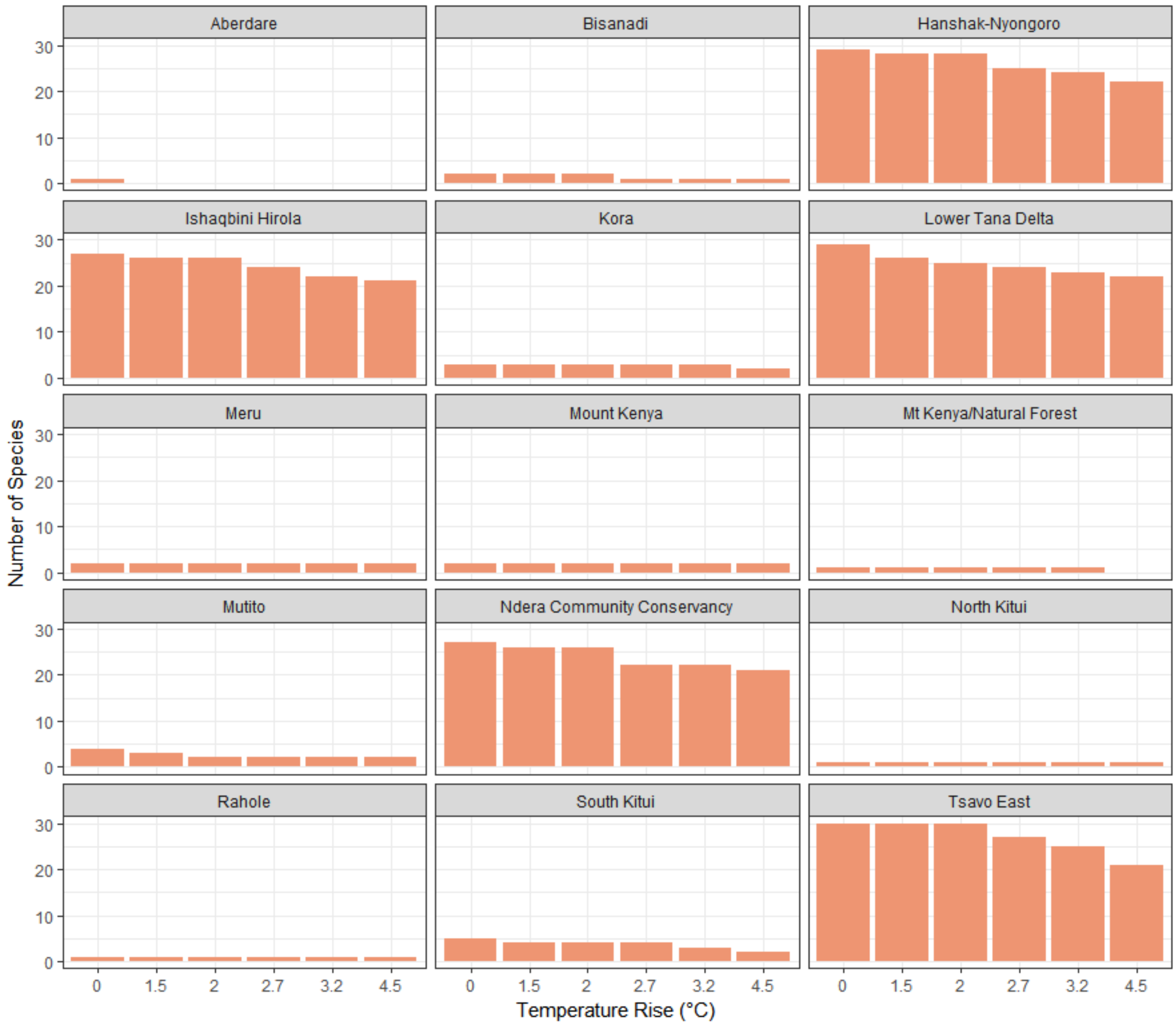

Figure 6-37: The number of case study plants present in the protected areas with different levels of warming

6.5.7 Which additional areas are needed for biodiversity protection?

5.5.7.1 Case Study Species

Although the PA network has been shown to be important for conserving species, there are some case study species that are not projected to be fully protected by these spaces. Figure 6-38 shows the number of animal species in each cell with 4.5°C of warming with no dispersal compared to the locations of the PAs. The 'no dispersal' scenario was chosen here because of the greater losses associated with this scenario shown in the previous sections. It is clear that the south of the basin still contains a large proportion of the case study animals, but that this area is only partially covered by PAs. The land between the Tsavo East National Park in the Southwest and the Hanshak-Nyongoro Community Conservancy in the Southeast is important for all four taxa. The highest number of mammals or birds in a single cell is lower than for current climate conditions (which was shown in Figure 6-23).

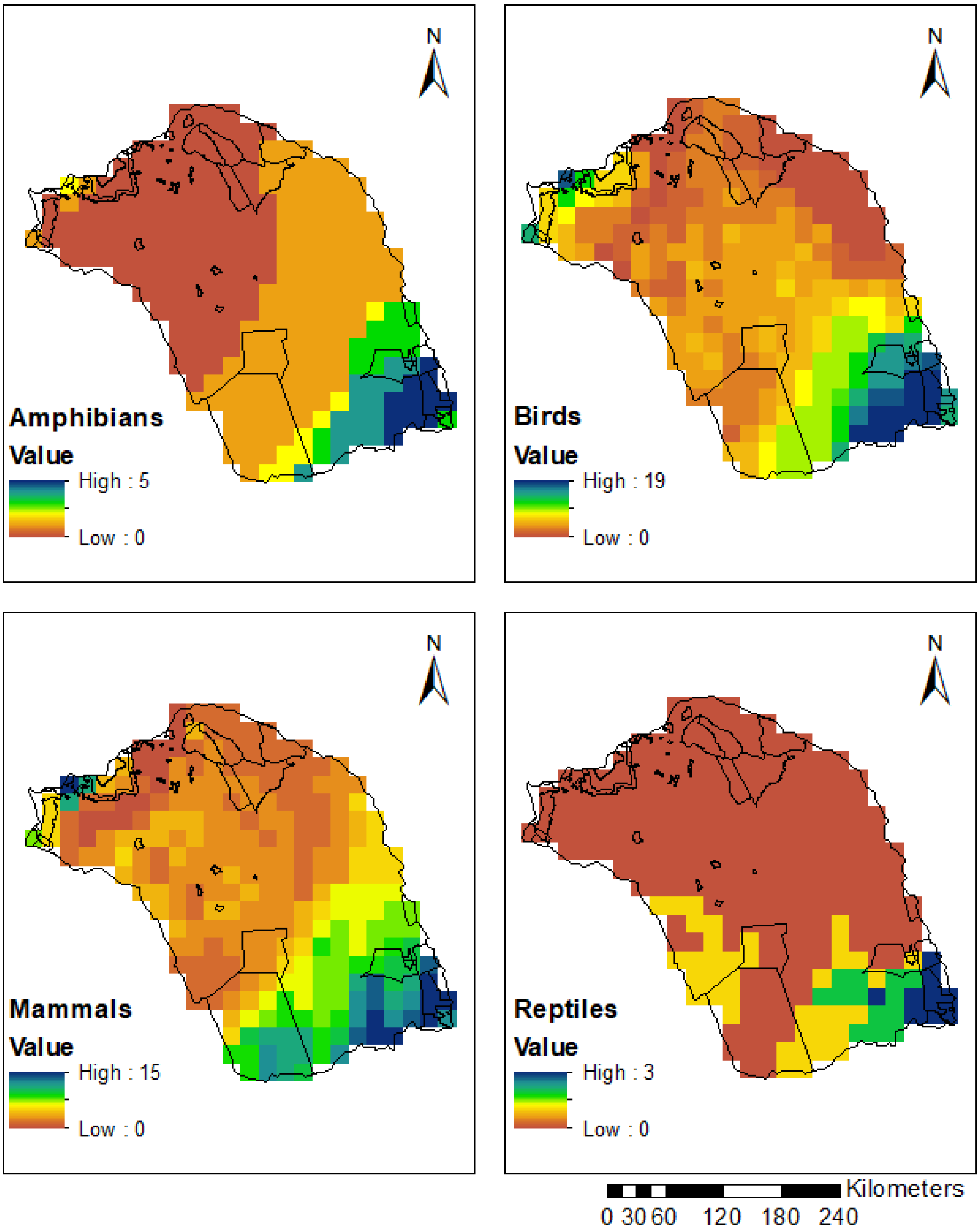

Figure 6-38: Number of case study animals present with 4.5°C warming with no dispersal. Black outlines show the current protected areas. Data are presented as the mean across 21 alternative climate models.

A similar spatial pattern is seen for plants in Figure 6-39. Again, the area between the Tsavo East National Park and the Hanshak-Nyongoro Community Conservancy is important. The highest number of case study plants in a single cell is 19. Under current conditions, the highest number of plants in a single cell was 29 (Figure 6-24).

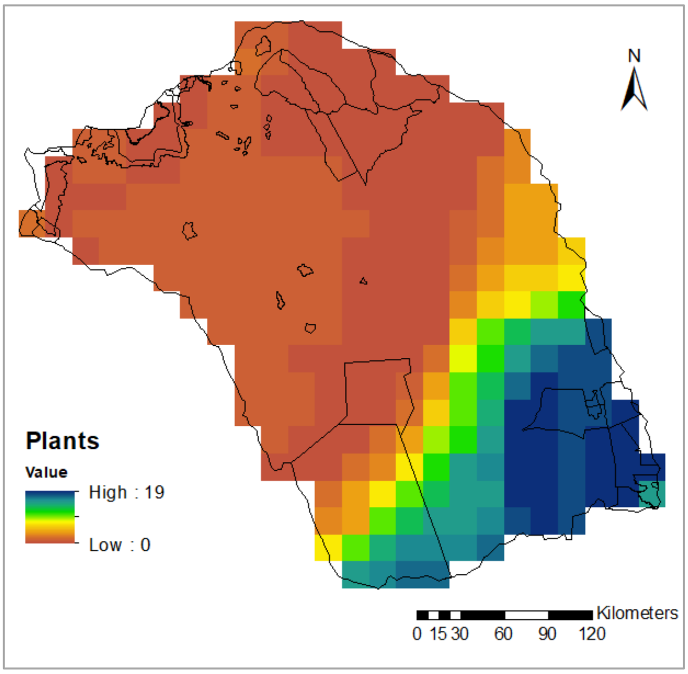

Figure 6-39: Number of case study plants in each cell with 4.5°C warming. Black outlines show the current protected areas. Data are presented as the mean across 21 alternative climate models.

When dispersal is allowed, cells in the southern basin remain suitable for a greater number of birds and mammals, as shown in Figure 6-40. As seen with the no dispersal scenario in Figure 6-38, the PAs do not cover all the cells that are most suitable for the case study species with warming.

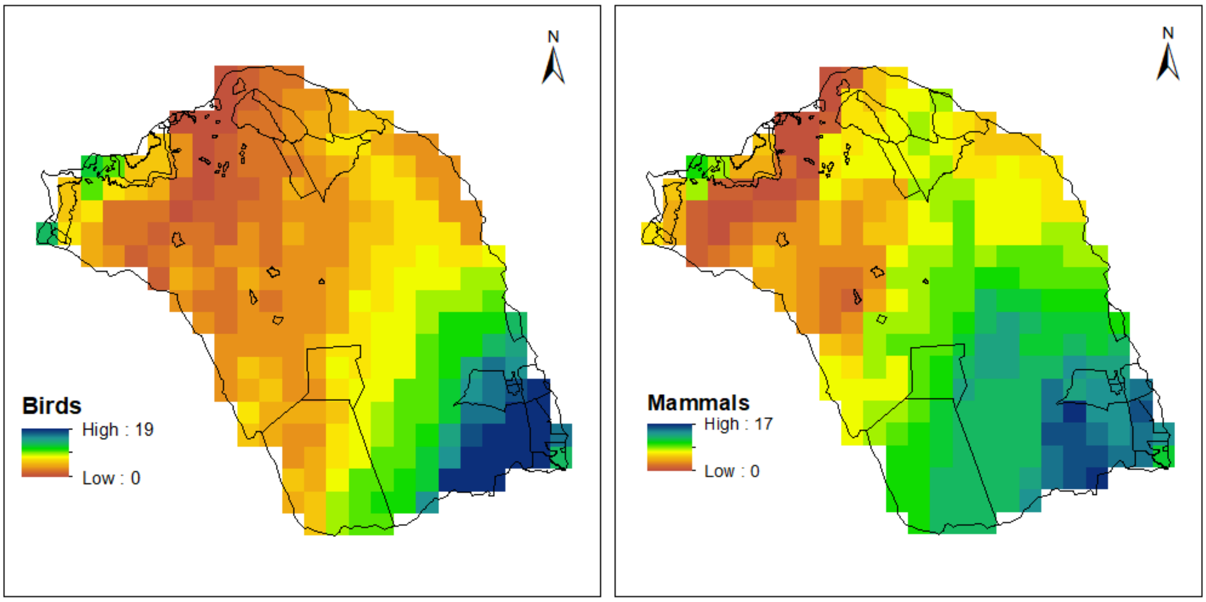

Figure 6-40: Number of case study birds and mammals present with 4.5°C warming with realistic dispersal. Black outlines show the current protected areas. Data are presented as the mean across 21 alternative climate models.

The difference between the two dispersal scenarios (realistic dispersal – no dispersal) are shown in Figure 6-41. Allowing case study birds to disperse is shown to be particularly beneficial in the northwest of the basin (i.e. the greatest difference between the two dispersal scenarios occurs in the northwest). By contrast, dispersal is particularly important for mammals in the central Tana River Basin. Maintaining connectivity in these areas is important to facilitate this movement.

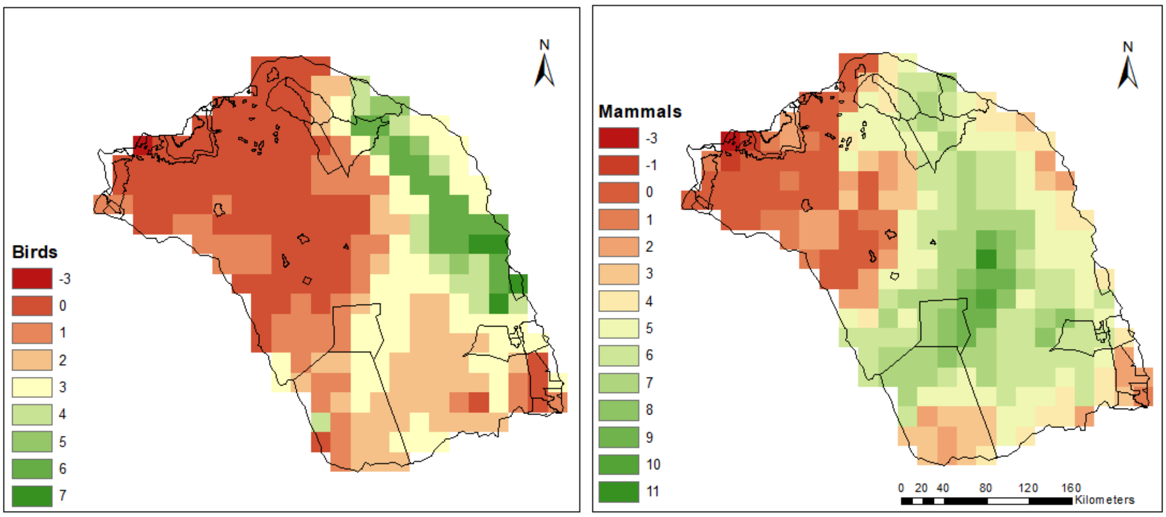

Figure 6-41: Difference between realistic and no dispersal scenarios for the case study mammals and birds. Black outlines show the current protected areas. Data are presented as the mean across 21 alternative climate models.

By considering the figures above, it is possible to propose a new PA, which would help protect the case study species in a changing climate. Figure 6-42 shows the location of the proposed new PA; in the south of the basin, between the existing PAs and where the greatest number of case study animals are projected to find suitable land in a changing climate.

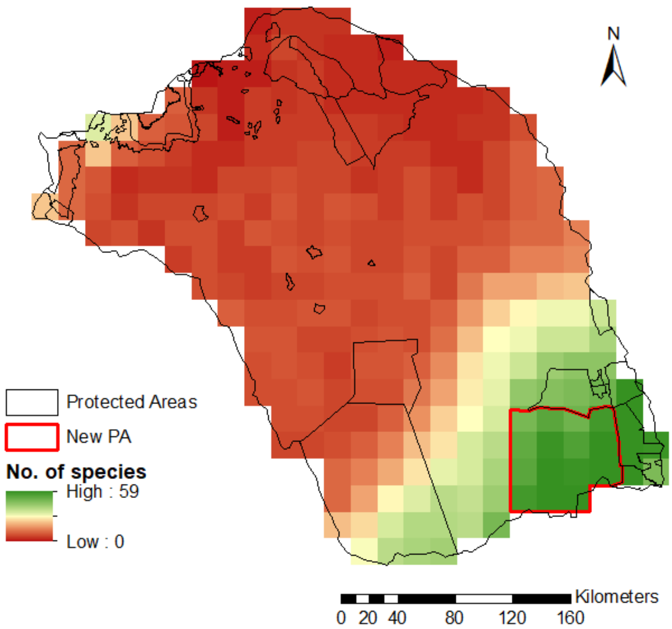

Figure 6-42: Proposed new protected area, with the number of case study species (all plants and animals) in each cell with 4.5°C with no dispersal. The current PAs are shown as black outlines.

5.5.7.2 Taxa Level

As well as considering the case study species, it is possible to propose new PAs at the taxa level. Figure 6-43 shows the locations of possible refugia for animals for RCP8.5 by the 2050s with the current and proposed PAs. The red outline shows the area identified as important for the case study species in the previous figure. Around half of the individual models project this area to contain refugia for the animal taxa. Another additional new PA is proposed in the east of the basin (shown in Figure 6-43 with a pink outline). This area is protected to contain refugia for all four animal taxa for RCP8.5 by the majority of GCMs. Figure 5-44 shows that this area could also contain refugia for plants, although there is less agreement between the models.

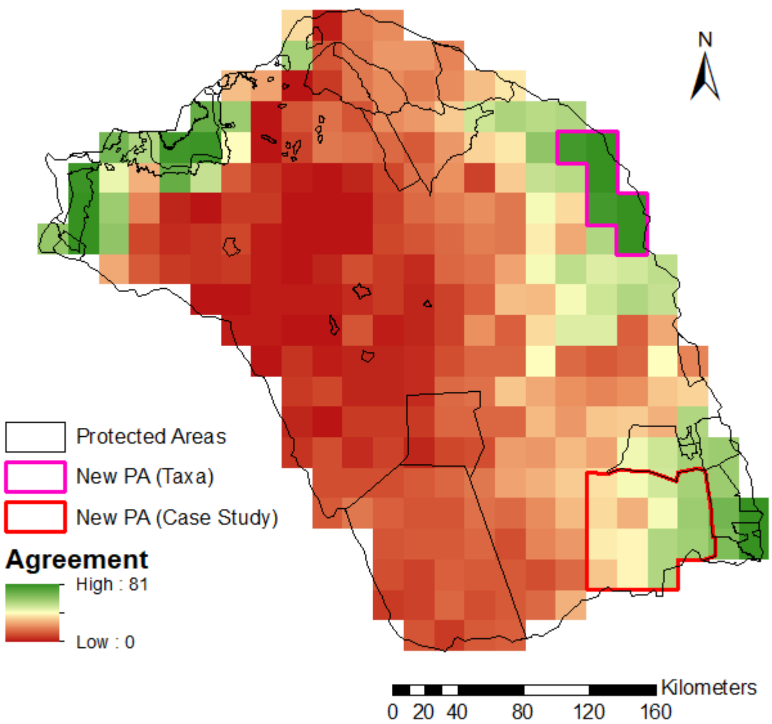

Figure 6-43: Number of models agreeing on refugia for animals for the 2050s compared to the proposed new protected areas. Pink outline shows the taxa level PA and the red outline shows the PA for the case study species

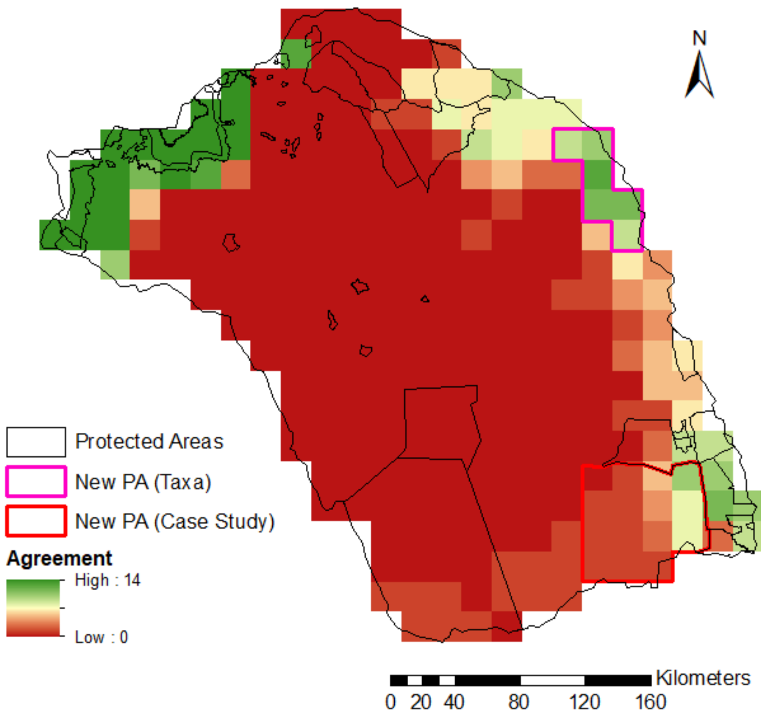

Figure 6-44: Number of models agreeing on refugia for plants for the 2050s compared to the proposed new protected areas. Pink outline shows the taxa level PA and the red outline shows the PA for the case study species

6.6 Discussion

6.6.1 Taxa Level Changes to Species Richness

Under current climate conditions, the highest values of species richness for all taxa were located in the Upper Tana Basin and in the Tana Delta. Assuming no dispersal, the results predict strong negative trends in species richness across the taxa. The reduction in average species richness seen in these results is consistent with global-scale studies (Warren *et al.*, 2013b; Foden *et al.*, 2013; Settele *et al.* 2014).

Amphibians are often strongly impacted by changes to their environment, especially in riparian areas. As a result of their sensitivity, they are often used as biological indictors of human disturbance (Carneiro *et al.*, 2016). Amphibian populations have been declining for several decades, partially as a result of habitat alteration and partially through disease outbreaks (Stuart *et al.*, 2004, Wake, 2007). These results do not show significant differences between the RCPs for amphibians in the 2020s, but this changes towards the end of the century. This suggests that amphibians are sensitive to the higher levels of warming projected to occur by the end of the century. It should be noted that amphibians are an extremely diverse group and sensitivity to climate is likely to vary between the species. Reptiles are also highly sensitive to changes in temperature as a result of their ectothermic characteristics. Bohm *et al.* (2016) found that over 80% of the reptiles included in their study were highly sensitive to climate change. However, there are not large differences in the proportions of species remaining between the different RCPs seen in these results.

At the taxa level, plants have been shown to be extremely vulnerable to climate changes. Reductions in the proportions of plants will affect the animals relying on them for food and habitats. The majority of refugia for plants can be seen in the mountainous regions in the north of the basin. This also has important implications because these montane species could be particularly vulnerable. As the climate warms further and these species reach the top of the mountains, not only will their geographic range become more constrained, but they will be unable to move any further, which could lead to localised extinctions. Endemic plants are likely to be more at risk than some endemic animals as they are unlikely to be able to disperse fast enough and may require human intervention in order to move.

Differences between the two dispersal scenarios for mammals and birds are marked. As with the other taxa, large losses are projected if species are not able to disperse. A greater proportion continue to inhabit the areas which are already climatically suitable if dispersal is allowed. This highlights the benefit of allowing species to move with the climate, which can be considered an adaptation measure.

Data on the relative importance of temperature and precipitation factors in determining changes to the distribution of species is not available in the Wallace Initiative database. However, Warren *et al.* (2013b) found that the distribution of over 50% of species analysed in each taxa were more strongly affected by temperature-related factors than by precipitation.

6.6.2 Refugia and Conservation Areas

Refugia exist within the Tana River Basin, demonstrating the importance of protecting the area. Two dispersal scenarios were compared for mammals and birds and significant differences between the proportions remaining under these scenarios was found. Even assuming realistic dispersal rates for mammal and bird species, their movement will be affected by habitat fragmentation, competition and the location of food sources. There are no large AOCs, where fewer than 25% of the species remain. There are fewer refugia for plants than for animals. Price *et al.* (2013) found a similar situation by examining refugia for plants and animals at the global scale. It was shown in Chapter 3 that the majority of GCMs project wetter annual future conditions in the Tana River Basin. This may go some way to explaining the relatively large number of refugia for amphibians. Water availability is extremely important for amphibians in the breeding season. With drier future conditions, the reduction in amphibian richness would likely be significantly higher, as dry periods are associated with high mortality in amphibians (Pounds *et al.*, 1999).

Some refugia for all taxa are within existing PAs, such as those around the Mount Kenya National Park and the Tana Delta Conservancy. However, some other important PAs, such as the Tsavo East, are likely to see decreases in the number of species remaining in the future. The Tsavo East is one of Kenya's oldest PAs. Changes to the species richness are projected to alter the conservation value of PAs (Wiens *et al.*, 2011). This may mean that existing PAs should be expanded to allow for species movement. Price *et al.* (2013) argue that the reductions in species richness could be a measure of adaptation deficit. Greater adaptation and conservation efforts will be needed for areas where more species are lost. However, problems are likely to occur in PAs that cannot be considered refugia. Many large mammals, such as the African elephant and hippopotamus, are already largely confined to PAs (Chamaille-Jammes *et al.*, 2013) as a result of human activity in other suitable areas. Without wildlife corridors to more suitable areas, these species may be forced to remain in PAs that become increasingly unsuitable for them. The GoK (Ojwang' *et al.*, 2017) has recognised the importance of maintaining wildlife corridors and dispersal areas. These results stress the need to plan for trans-situ conservation to account for moving species.

6.6.2.1 Do the PAs preserve the case study species?

The existing PA network is shown to be important for the species of interest. The Tsavo East National Park and the Hanshak-Nyongoro Community Conservancy are the most important PAs for the mammal and bird species analysed here. Ojwang' *et al.* (2017) also noted the importance of the area surrounding the Tsavo East National Park, particularly the neighbouring Galana and Kulalu Ranches as wildlife movement corridors.

Many of the case study species are present in the PAs with climate change. Buffalo (*Syncerus caffer*) are present in many PAs under current conditions. With realistic dispersal, more PAs become suitable in the future with higher temperatures. However, droughts in the Tsavo reserves have previously impacted the numbers of buffalo (Bennitt *et al.*, 2014), showing that they will be sensitive to extreme weather events as well as changes to the mean temperature. With reductions in rainfall projected for the dry season by the multi-model mean scenarios (Chapter 4, Section 5.3), it is likely that this area of Kenya will continue to experience droughts in the future.

Ojwang' *et al.* (2017) maps key populations of elephants and finds that they occur both inside and outside the PAs around the coast and in the mountains of the north of the basin. Areas suitable for African elephants are currently found in Meru, Tsavo East, South Kitui and the Hanshak-Nyongoro Community Conservancy. With higher temperatures, assuming no dispersal, most of these PAs are no longer suitable for elephants. If realistic dispersal is included, the Ndera Community Conservancy also becomes suitable for elephants. Epps *et al.* (2011) found that giraffes and lions are restricted to PAs and showed low connectivity. Elephant presence was negatively correlated with human population density, farming and elevation. Maintaining elephant corridors can help protect habitat connectivity for other species.

For this analysis, it was assumed that all of the species that had suitable climate space within the PAs, both under current conditions and with temperature rise, are protected in these spaces and occur in viable populations. Although this might not be the case, this assumption allows for the identification of species that require more future conservation attention (i.e. those not occurring at all within the PAs).

Protecting additional areas in the south of the basin, between the Tsavo East National Park and the Hanshak-Nyongoro Community Conservancy, would be beneficial for many of these species. Even with the highest levels of warming, many of the case study species, including the leopard, elephant and giraffe, still have suitable climate space in this area. Some of this land is already an EBA, so its importance for bird species is already recognised.

6.6.2.2 Comparison with Taxa Level Results

The reductions in the areas suitable for the case study species corresponds to the reductions shown in the taxa level results. Hanshak-Nyongoro Community Conservancy, Ishaqbini Hirola Community Conservancy, the Lower Tana Delta Conservation Trust and Ndera Community Conservancy were shown to be refugia for animals. These PAs are all in the south of the basin, along the main Tana

River. The results of the case study species support this. The number of the identified species that these PAs remain suitable for remains relatively high. This suggests that protecting the refugia will help ensure the survival of many of the case study species.

However, it was also possible to identify additional areas that might benefit from greater protection (Section 6.5.7). At the taxa level, an area in the east of the basin along the main Tana River was projected to be refugia for animals and plants by the majority of climate models. This was not identified as particularly important to the case study species, suggesting that protecting land here may benefit other species; many of which would currently be less threatened than those included in the case study.

6.6.3 Benefits of Dispersal to Biodiversity Conservation

The importance of allowing species to move with the changing climate is clearly shown by these results. A full list of case study mammals and bird species with increasing climate suitability within the basin with realistic dispersal rates is provided in Appendix V. The climate becomes more suitable for ten birds and nine mammals with 2°C of warming if these species are allowed to disperse. Additional PAs become suitable for some birds and mammals with higher temperatures. However, it should be considered that if temperature thresholds are met early, which may be the case with 1.5 and 2°C of warming, many species would not have had sufficient time to disperse. In addition, blocked wildlife corridors would form barriers to species movement. The fragmented landscape may prevent many species from moving to more suitable areas. Removing barriers to movement could prove an important climate change adaptation measure in Kenya.

6.6.4 Benefits of Mitigation to Biodiversity Conservation

There are clear benefits of mitigation (i.e. the reduction of GHG emissions) to the preserving the biodiversity of the Tana River Basin. For the BAU scenario, there are substantial reductions in the number of species present in the PAs, as well as significantly fewer suitable cells for many animals. The number of cells and PAs that remain climatically suitable is higher when warming is limited to 1.5 or 2°C. For most species, the benefits of mitigation are greater than the benefits of dispersal. A greater suitable area remains for 2°C and no dispersal than with 4.5°C where dispersal is allowed. Constraining warming allows more species to continue inhabiting areas that are already (currently) suitable. A comparison between the proportions of the current suitable area within the basin that remains suitable for each species is included in Appendix V. This was also shown at the taxa level, as larger areas are considered to be refugia for RCP2.6 than RCP8.5.

6.6.5 Case Study Species in need of Additional Conservation Attention

A list of the case study species with no suitable climate space remaining with the basin is provided in the Appendix V. Nearly all case study species retain some suitable climate space with temperature increases of up to 3.2°C but 15 species are lost from the basin with 4.5°C of warming, assuming no dispersal. This includes one mammal, one reptile, six plants and seven birds. The situation is the same for the mammal (African wild dog) and birds both with and without dispersal. None of the case study amphibians are particularly vulnerable to climate change.

There are many more mammals whose suitable climatic space becomes extremely limited with 4.5°C of warming. *Giraffa camelopardis*, *Panthera leo*, *Acinonyx jubatus*, *Damaliscus lunatus* and *Otomops martiensseni* all lose at least 90% of their current suitable range within the basin without dispersal. Of the birds, *Struthio camelus*, *Torgos tracheliotus*, *Trigonoceps occipitalis* and *Gyps africanus* lose 90% or more of their current suitable area within the basin without dispersal.

Additional areas that should be protected in order to conserve the case study species have already been identified and discussed in Section 5.5.7.1. The area in the south of the basin between the Tsavo East National Park and Tana Delta were found to be of particular importance for the case study species. This area near the coast is one of the few areas of Kenya that continues to boast a large population of topi (Ojwang' *et al.*, 2017) so losing the species from this area would be significant. These results show that topi are likely to decrease in a changing climate so may be in need of additional conservation action.

Furthermore, some of these species are already experiencing other threats which will interact with the effects of climate change. The Basra reed warbler overwinters in the Tana River Delta and so is also threatened by the large-scale agriculture projects planned for the area (BirdLife International, 2017). Without suitable PAs in this delta region being suitable for the species, the reed warbler may not be able to overwinter in the basin. It is helped a little if dispersal is feasible, but limiting warming (mitigation) would be particularly beneficial for this species.

6.6.6 Implications for Tourism

These changes to the biodiversity of the Tana River Basin will have implications for tourism. Arbieu *et al.* (2017) found that visitor numbers in selected PAs in South Africa, Namibia and Botswana were higher in areas where there was high predator species richness and a presence of locally rare ungulate species. By contrast, the abundance of the Big Five species did not have a significant effect on visitor numbers. A high diversity of large mammals was also found to be important in attracting high numbers of wildlife tourists. Although this study only examined mammals, the results may have implications for future tourism in Kenya. The PAs within the Tana River Basin generally saw a decrease in suitability for many of the predator species examined here, such as the wild dog, cheetah and African lion. Similarly, a reduction in the number of species in the PAs with climate change could impact tourist numbers. This could be particularly significant for the Tsavo East National Park, which could experience reductions in the number of species present in the future. Other than the Masai Mara, the Tsavo ecosystem is the most popular with tourists (Ojwang' *et al.*, 2017), so it is a good example of an area on which to focus conservation resources.

6.6.7 Limitations

An important assumption made with species distribution modelling is that the distributions are limited by climate. However, climate is only one component of the risk that species face. Pearson and Dawson (2003) created a scale of relevance for the different factors that influence species distribution. At the regional scale, climate and topography are shown to be the most influential. As analyses move towards more local scales, land-use, soil type and biotic interactions are shown to become increasingly important. Due to the size of the Tana River Basin, this study can still be seen as regional and therefore climate is still a very relevant factor. Due to the spatial scale of datasets used for this work, local scale influences, such as soil type and biotic interactions, cannot be taken into account.

In addition, uncertainties arise during the modelling process. SDMs can be overfitted, which can lead to flawed outputs by limiting the model's capacity to generalise. SDMs cannot include and account for all biotic and abiotic factors. The ability of a species to migrate at a sufficient rate to keep up with the changing climate will be dependent on the dispersal characteristics of that individual species (Collingham and Huntley, 2000). Therefore, dispersal rates may not be representative of all the species included. Similarly, barriers to movement, interactions between species, the ability of species to use novel climate spaces and the effects of extreme weather events cannot be included. Even though various uncertainties exist, SDMs are extremely useful for examining the future impacts of climate change on species. This knowledge is fundamental for policy-makers and conservation planners.

There are also a number of specific caveats which also need to be taken into account. It is important to consider the current number of species present when interpreting the results for the different taxa. The results for amphibians and reptiles are based on fewer species and should be considered less certain. It is also likely that many species present in the basin have not been included in the database. For instance, 33 reptiles and amphibians native to Kenya are classed as EN, VU or NT on the IUCN Red List, but only 5 were present in the Wallace Initiative database. Some of the species of interest identified through the literature review were not present in the Wallace Initiative records, such as the endemic primate species the Tana River Red Colobus and the Tana River Mangabey. However, primate abundances are highly correlated with the spatial characteristics of the forest (Medley, 1993) and therefore by examining their main habitat and food species, this analysis goes some way to examining the effects future climate change may have on them. In addition to some known species being absent from the database, there may be undiscovered species present in the area that cannot be accounted for. Meng *et al.* (2016) indicated that new species of reptiles are still being discovered in Eastern Africa.

Moreover, the 8 parameters chosen for the Wallace Initiative may not be those that have the greatest influence on all animal, native plant and agricultural species. For future research, MaxEnt could be run for these species to determine this.

Due to the spatial scale used in the Wallace Initiative, it is possible that some cells that become unsuitable for many species may actually contain micro-refugia within them. Similarly, cells classed as refugia may have AOCs within them. Price *et al.* (2013) acknowledged this limitation but justified the spatial scale used as appropriate for global-scale work and also showed that these two effects may cancel one another out. Similarly, the fact that the smallest PAs could not be included in this analysis is also a limitation. These PAs may provide micro-refugia in some cells.

There are other relevant factors that have not been included in this analysis, predominantly due to the spatial scale used in the Wallace Initiative database. The potential spread of disease pathogens would impact the survival of species and pests and diseases may also change with climate change. Furthermore, changes to the distributions of species may lead to a de-coupling of trophic levels. Tylianakis *et al.* (2008) argue that adding tropic level interactions to models will be one of the major upcoming challenges for ecology. Climate change may affect food availability, predator-prey relationships and competitive interactions between species. Kioko *et al.* (2006) found that, in the dry season, elephants within the Tsavo ecosystem are primarily found within *Acacia xantophloea* and *Acacia tortilis* woodland, where they have preferred food sources. Alterations to these species in a changing climate may affect elephant habitats and locations. Similarly, Acacias have also been shown to be an important food source for giraffes (Parker and Bernard, 2005). Thuiller *et al.* (2006) found that changes in community structure could be a more destructive result of climate change than the loss of species from their current ranges.

The direct biotic effects of increases in CO_2 concentrations on plants have not been considered. Elevated CO_2 could lead to increased plant growth and a reduction in water usage. Higher CO_2 concentrations could lead to earlier stomata closing. Plants regulate their stomatal opening to ensure a balance between high rates of photosynthesis and low rates of water loss. Recent studies have also linked increased CO_2 concentrations to a shift from African grassland and savanna to more densely vegetated woodland (Higgins and Scheiter, 2012). With elevated CO_2 concentrations, some plants are more able to maintain high photosynthetic rates with lower stomatal conductance. Changes to protein concentrations may lead to plants being of less nutritional value to the herbivores. This could lead to increased consumption to compensate for the reduction to food quality (Stiling and Cornelissen, 2007). It is also important to remember that a plant's ability to benefit from higher CO_2 concentrations may be limited by the availability of other essential minerals. Including these effects would not be practical in a study of this size (Warren *et al.*, 2013b) and the complex nature of the possible effects of higher CO_2 mean that the changes are still uncertain.

Alternations to extreme climatic events have not been included but could put significant pressure on species (McDermott-Long *et al.*, 2017, Parmesan *et al.*, 2000). Heat waves or droughts may exceed the thresholds for survival for a range of species, which could result in species loss within an area where the mean climate is still suitable. It is likely that some species examined here will be more sensitive to the climate extremes. In addition to heat and drought, severe storms and storm surges may affect species close to the coast. Palmer *et al.* (2017) showed that species' responses to extreme climatic events is extremely individualistic and that some responses are delayed. Including these individualistic responses in this study was not feasible due to the large number of species studied.

The PAs and species' ranges extend beyond the Tana basin, as shown in Figure 6-45. The Tsavo East National Park is an example of these. Other areas of the Tsavo East or the connected Tsavo West and Amboseli National Parks may remain more suitable for species in the future. Contrastingly, some PAs within the Tana River Basin are extremely small and changes cannot be seen at the scale of this analysis. Examples of these are the Lusoi and Thunguru Hill forest reserves in the north of the basin close to the Mount Kenya National Park and Ngamba forest reserve to the north of South Kitui.

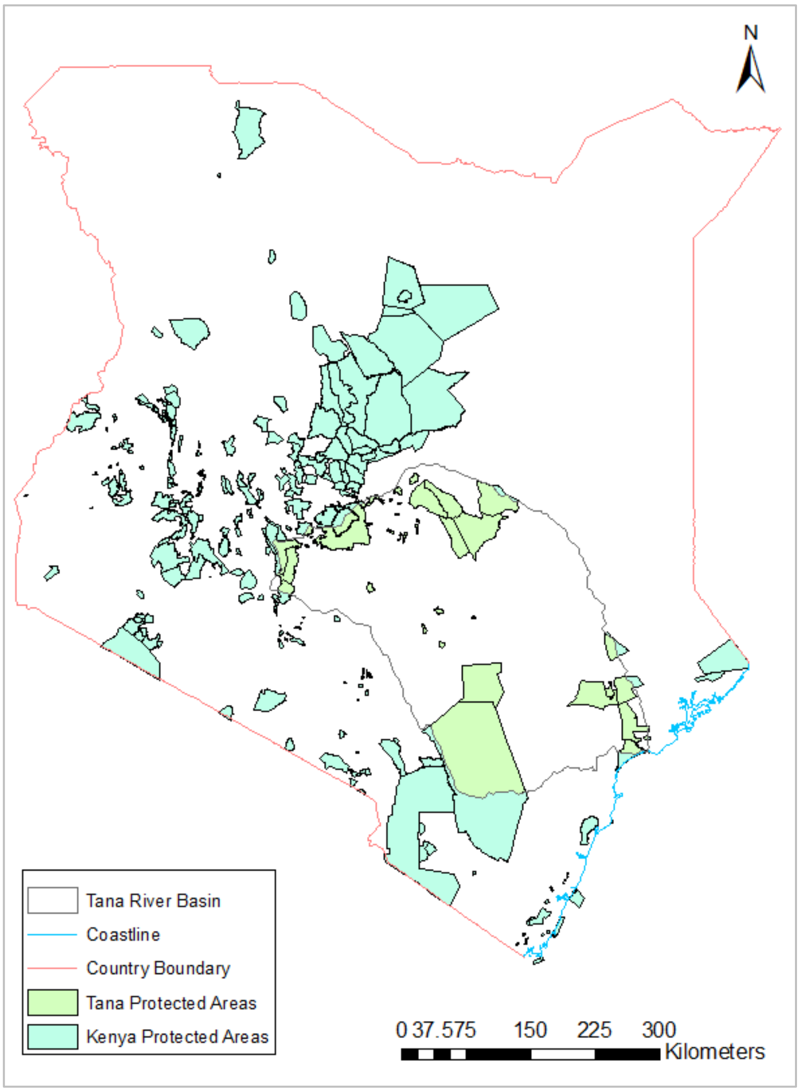

Figure 6-45: Protected Area network for Kenya, with those within the Tana River Basin in green. (Protected areas dataset from IUCN and UNEP-WCMC, 2016)

6.7 Chapter Summary

This chapter has presented results on the impacts of climate changes on the distribution of biodiversity in the Tana basin and clearly illustrates climate-induced shifts in species ranges in this area of Kenya. Refugia have been identified for all taxa, though fewer exist for plants. Two dispersal scenarios were compared for mammals and birds and significant differences between the proportions remaining under these scenarios was found. The benefits of allowing species to move with the climate are clear, as are the benefits of limiting warming (mitigation). Some existing PAs were found to be refugia, while others experienced larger losses in species richness. Case study species were identified and analysed. The current PA network was found to be insufficient for protecting all of the species with higher levels of warming. Even under current conditions, there are areas in the south of the basin with a particularly high species richness that are not covered by the PA network.

These results may be over- or under-estimates due to uncertainties in the models and the effects of factors such as extreme weather, interactions between species and species' abilities to occupy novel climates, which were not considered.

The following chapter will combine projections of future climate with changes in land use and land management. It will examine the key policies relevant to the basin, before discussing the implications of changes for biodiversity and water resources.

Chapter 7 Changes to Land Use and Agriculture

7.1 Introduction

The aim of this chapter is to explore the impact of land use and land cover change (LUCC) on the Tana River Basin and to combine this with previous results on changes to water resources and biodiversity caused by future climate change. The structure of this chapter is explained in Figure 6-1. First, this chapter will consider how land cover in Kenya has been changed by human use in the recent past, showing some of the causes of this land use change (Section 2). This chapter will examine a variety of datasets, including projections of changes to yields of major crops from the ISI-MIP Fast-Track database and smaller used species included in the Wallace Initiative database. This addresses Objective Ib. Again, a range of projections are considered to address Objective IV. The methods are presented in Section 3. Then, results of the different analyses are presented in Section 4. Section 5 integrates the results within and across sectors; bringing together the different analyses presented in this and the previous three chapters. The implications of these findings are discussed in Section 7.

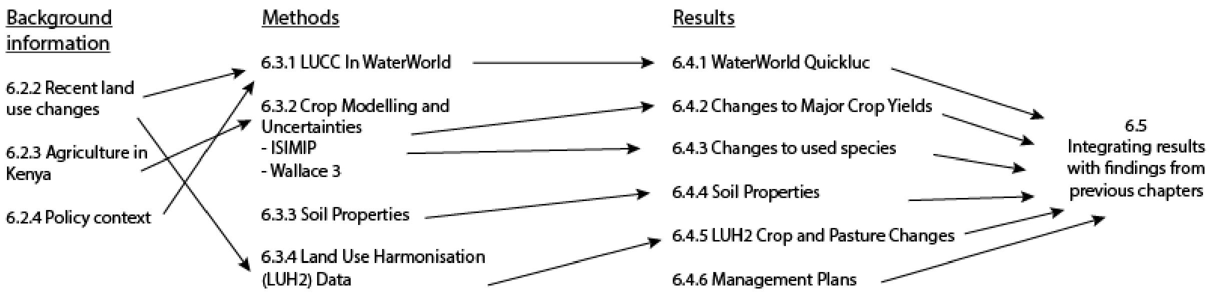

Figure 7-1: Structure of this chapter

7.2 The importance of Land Use and Agricultural Development

Land is needed for human habitation, conservation of biodiversity, agriculture, energy production, transportation and environmental amenities. However, it is a finite resource and competition for land is an important contemporary topic of research and policy.

7.2.1 The Importance of Land Issues in Kenya

Land use is a very important and emotive issue in Kenya (Sifuna, 2009), as the majority of the population still rely on the land for their livelihoods. Land is often cited as the most important resource in Kenya and management of land as one of the most critical challenges the country faces (Kang'ee, 2015). Until recently there was no comprehensive land use policy in Kenya. The new policy is still being implemented and land grabbing – large-scale acquisitions of land – still occurs. The Government of Kenya recognise land grabbing as a development problem, but it is still done by both the Kenyan elite and foreign investors. Duvail *et al.* (2012) highlight a remaining problem with land use designation in Kenya; namely that projects designate floodplains as unused land which is available for development. The importance of the ecosystem services which these areas provide are not considered and land grabbing now includes important ecosystems such as forests and wetlands (Duvail *et al.*, 2012). Much of the land in Kenya has been converted for agriculture, which is central to Kenya's economy. It is the leading sector in terms of its contribution to both GDP (contributing to around 24%) and employment (around 70% of the country's labour force). Unlike many global agricultural regions, recent development in Kenya has been achieved through the expansion of agricultural lands rather than improving the efficiency of the existing agricultural land (Alila and Atieno, 2006).

7.2.2 Recent Land Cover Change

Recent land cover changes in Kenya are dominated by a reduction in forest cover as a result of agricultural expansion. Hogarth *et al.* (2015) show that agricultural expansion accounted for approximately 70% of forest loss between 2000 and 2010. Much of this forest loss has occurred in the Tana River Basin, as shown in Figure 7-2. This shows the recent rates of forest loss, based on Hansen *et al.* (2013), who used Landsat imagery from 2000-2012 to characterise annual deforestation. Recent deforestation is concentrated in the northwest of the basin and around the basin outlet near Kipini. There is clear deforestation around the edges of the national reserves, particularly Mwingi and South Kitui National Reserves and Tsavo East National Park. Small pockets of deforestation can also be seen along the Tana River itself.

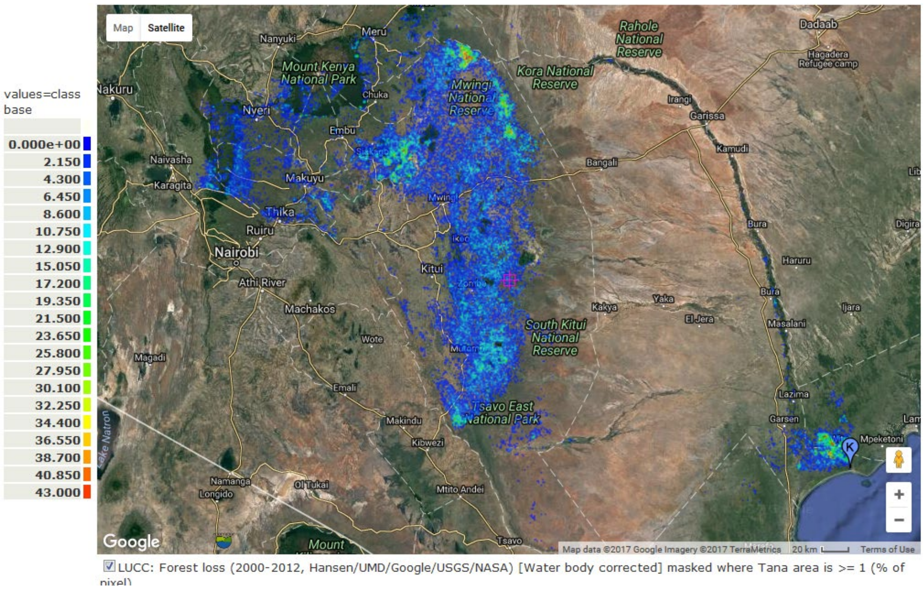

Figure 7-2: Percentage of forest loss within the Tana River Basin between 2000 and 2012. From Mulligan (2017) based on Hansen et al. (2013). Google Earth place marker 'K' shows the main outlet of the Tana River into the Indian Ocean at Kipini.

MODIS Vegetation Continuous Fields (VCF) can be used to provide information on the percentages of bare ground, tree and herbaceous cover in the basin (Hansen *et al.*, 2003). Figure 7-3 shows the current (2000) land cover in the Tana River Basin, from this MODIS data which is available through the WaterWorld model. The current land cover is dominated by herb-covered ground (mean: 78.7%). Only 6.7% of the study area is tree covered. Tree dominated areas are concentrated in the highest elevations and in the Tana delta region. The remaining 14.5% is classed as bare ground. Bare ground is largely found across the floodplains and on the lower ground in the centre of the basin.

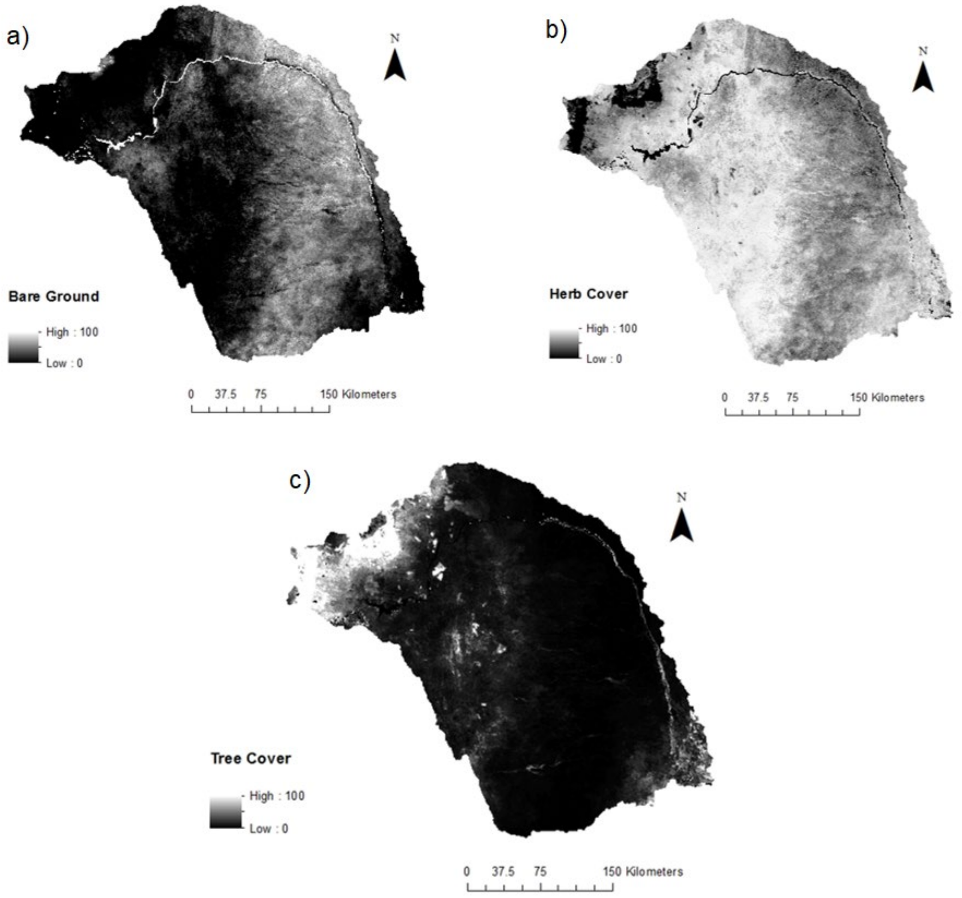

Figure 7-3: Baseline percentage land cover of the catchment (a) bare ground, (b) herb cover and (c) tree cover from the MODIS derived Vegetation Continuous Fields (VCF) (Hansen et al., 2003) and converted to percentages by Mulligan (2013b) for use in the WaterWorld model, as described in Section 6.3.1.

The following figures show observed changes in agricultural development in the Tana River Basin using global datasets available in and used by WaterWorld. These include the distribution of croplands (Ramankutty *et al.*, 2008; Fritz *et al.*, 2015), pastures (Ramankutty *et al.*, 2008; Obersteiner, 2015) and managed or wildland grazers (Wint and Robinson, 2007; Robinson *et al.*, 2013). These are important land uses and are also indicators of land degradation.

Figure 7-4 shows that pastures are spread throughout the Tana River Basin. National Parks, such as the Tsavo East in the southwest of the basin, have no pasture cover within them, but large proportions around the edges of the PAs. Figure 7-5 shows that the croplands predominately in the northwest of the river basin in the hilly, upland areas. The highest cropland fractions correspond to the areas of recent deforestation shown in Figure 7-2. The Mount Kenya National Park is free from croplands. It is also possible to determine the percentage of the basin that is cropland (13.8%) and pasture (28%). The relatively low percentage of cropland cover is consistent with official reports. The FAO (2003) shows that less than 30% of the land suitable for agriculture in Kenya has actually been cultivated.

In order to better examine pressures on land from cattle density, livestock densities are also included in the WaterWorld input data and are presented here (Mulligan, 2016). The proportions of livestock, either wildland grazers (Figure 7-6) or managed grazers (Figure 7-7), are relatively low throughout the basin. Livestock densities are calculated from Wint and Robinson (2007). Wildland grazers (Figure 6-7) include cattle, buffalo, goats and sheep. Small areas of intense grazing can be found in the north of the basin, to the east of the Mount Kenya National Park.

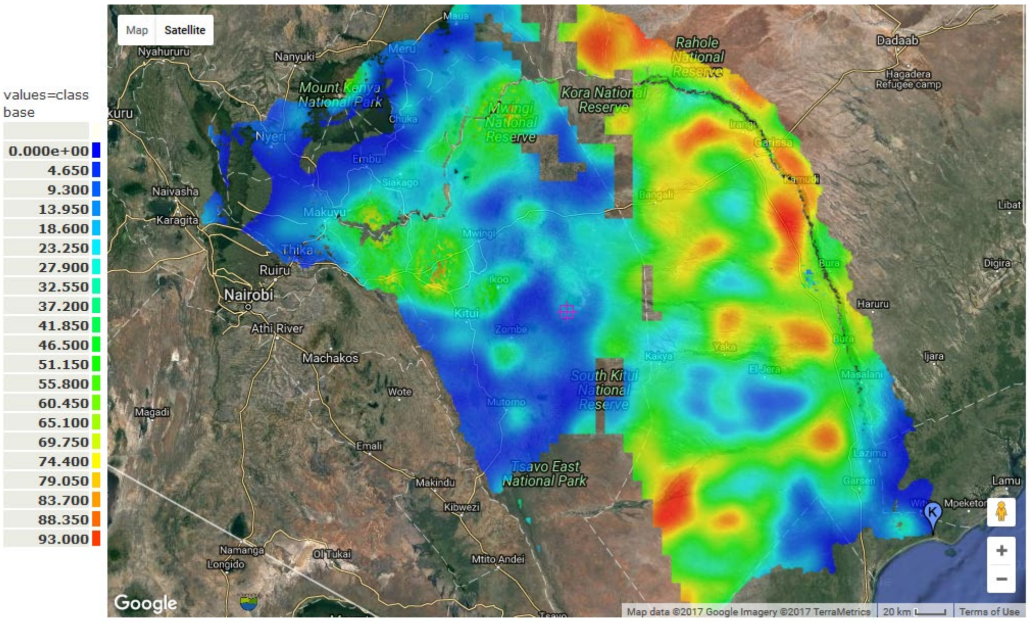

Figure 7-4: Pastures within the Tana River Basin, based on data from 2005. Percentage pasture cover within the basin ranges from 0-93%. Blue colouring shows a low percentage of pasture cover and red shows the highest percentage of pasture cover for a pixel. From Mulligan (2017) based on Ramankutty et al. (2008) & Obersteiner (2015). Google Earth place marker 'K' shows the main outlet of the Tana River into the Indian Ocean at Kipini.

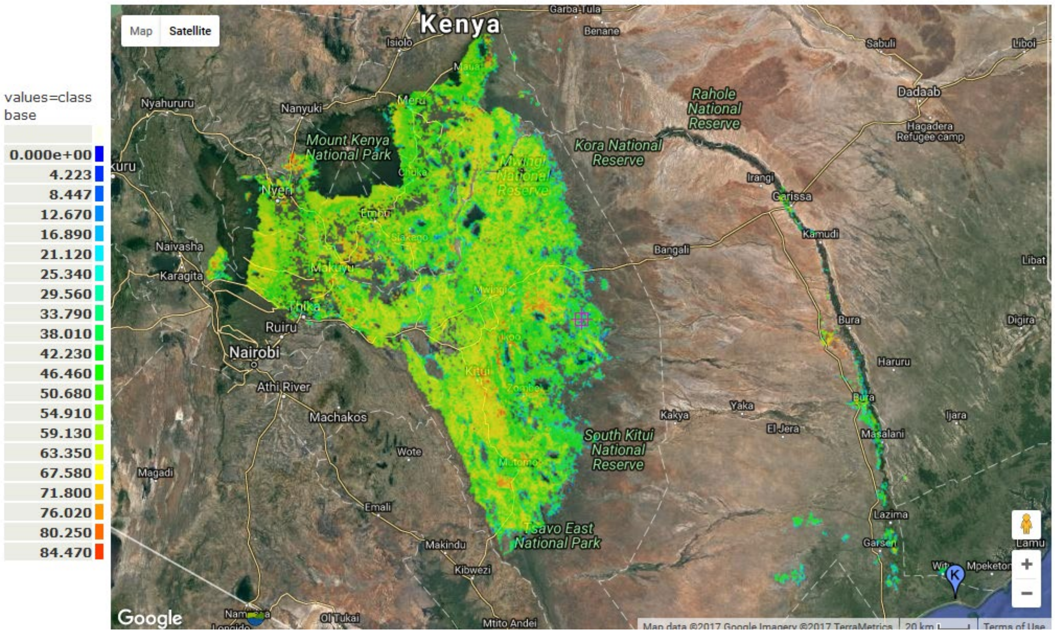

Figure 7-5: Croplands within the Tana River Basin, based on 2005 values. Percentage cropland within the basin ranges from 0-85%. Lowest cropland proportions are shown in blue and highest are in red. From Mulligan (2017) based on Fritz et al. (2015). Google Earth place marker 'K' shows the main outlet of the Tana River into the Indian Ocean at Kipini.

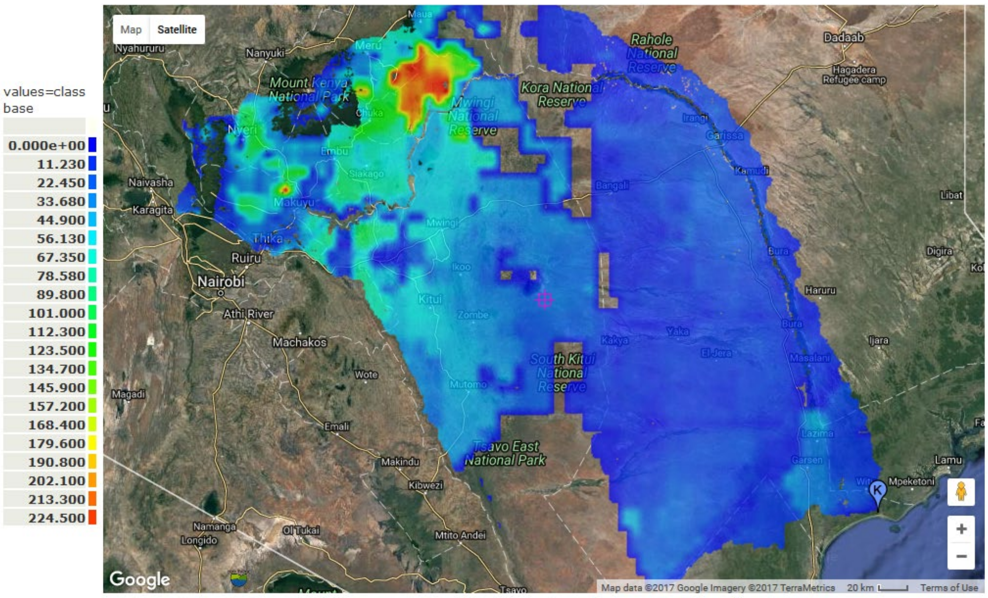

Figure 7-6: Wildland Grazing Livestock (headcount per km^2) within the Tana River Basin, based on 2005 values. Lowest concentration of grazing livestock are shown in blue and highest are in red. From Mulligan (2017) based on Wint and Robinson (2007). Data from: Gridded livestock of the world - Wildland Grazers. Google Earth place marker 'K' shows the main outlet of the Tana River into the Indian Ocean at Kipini.

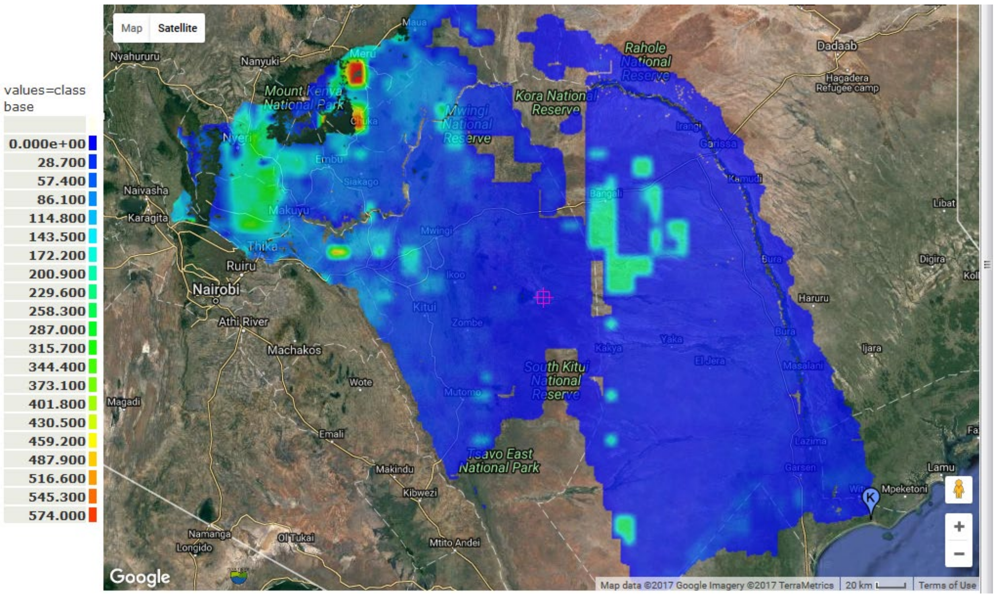

Figure 7-7: Managed Grazing Livestock (headcount per km²) within the Tana River Basin, based on 2005 values. Lowest concentration of grazing livestock are shown in blue and highest are in red. From Mulligan (2017) based on Wint and Robinson (2007). Data from Gridded livestock of the world – Managed Grazers. Google Earth place marker 'K' shows the main outlet of the Tana River into the Indian Ocean at Kipini.

Land use change in East Africa has released over 200 $MtCO_2$ per year in recent years (Houghton *et al.*, 2012). It is not just the conversion to agricultural land that needs to be considered. Pressure on land also comes from the rapidly-growing population and expanding urban areas. Population in Kenya is highly clustered around urbanisation, as with the global trend.

7.3 Methods

This analysis will use a range of datasets and methods. The main stages of analysis in this chapter are described in Table 7-1.

Table 7-1: The stages of analysis within this chapter showing the different steps and the chapter sections for methods and results

Step	Description	Methods Sections	Results Sections
1	Land use and cover change analysis in WaterWorld	6.3.1	6.4.1
2	Changes to crop yields from ISI-MIP	6.3.2.1, 6.3.2.2	6.4.2
3	Wallace Initiative for used species	6.3.2.3	6.4.3
4	Soil properties from the GAEZ database	6.3.3	6.4.4
5	LUH2	6.3.4	6.4.5
6	Comparison with management plans	-	6.4.6

7.3.1 LUCC in WaterWorld

WaterWorld has already been used to model changes to key hydrological variables with climate change. A full description of the WaterWorld model is given in Chapter 5, Section 2. WaterWorld was also used to assess the impacts of land use change. Policy support systems like WaterWorld allow users to examine the implications of adopting various policies but do not provide information on which policy would be best to adopt (Mulligan, 2016). Land use and water management scenarios were developed using policy documents that detail future plans, such as the Vision 2030 and the National Water Master Plan 2030 which were considered in Table 2-1.

7.3.1.1 How WaterWorld handles vegetation

WaterWorld uses the MODIS Vegetation Continuous Fields (VCF) to provide information on the percentages of bare ground, tree and herbaceous cover (Hansen *et al.*, 2003). Baseline values have already been presented in Figure 7-3. This VCF data has various advantages over land cover classifications, such as the Global Land Cover Characteristics (GLCC) database. Using VCF provides a much more precise treatment of vegetation, increasing the spatial detail and precision (Mulligan and Burke, 2005). WaterWorld uses the SimTerra database (Mulligan, 2013a), which includes agricultural land coverage including cereal crop fraction which has been extracted from the global crop areas and yields data of Ramankutty *et al.* (2008) called Croplands2000 (Pandeya and Mulligan, 2013).

The baseline tree, herb and bare ground percentages from MODIS VCF were converted to fractions for use in WaterWorld, as shown in Figure 6-2 (Mulligan, 2016). Through WaterWorld, it is possible to see the effects of simple changes in land cover. It is also possible to create more complex land cover change scenarios, through the QUICKLUC (version 2.3) deforestation model, which forms part of WaterWorld. QUICKLUC is an equilibrium model that projects deforestation on the basis of recently measured rates and allocates the deforested pixels based on distance-based rules (Mulligan, 2016). The recent rates of deforestation used in the QUICKLUC model are provided by FAO (2014) figures. The specific pixels changing can be allocated by agricultural suitability. If this option is selected, the allocation is controlled in part by normalised mean agricultural suitability for crops included in the IIASA GAEZ analysis. The management effectiveness of different scenarios can also be altered. A value of 1 represents a high management effectiveness, while 0 shows that the management practices are ineffective.

Different rules in the QUICKLUC model will produce very different results (Mulligan, 2016). An example of a QUICKLUC deforestation scenario is shown in Figure 7-8.

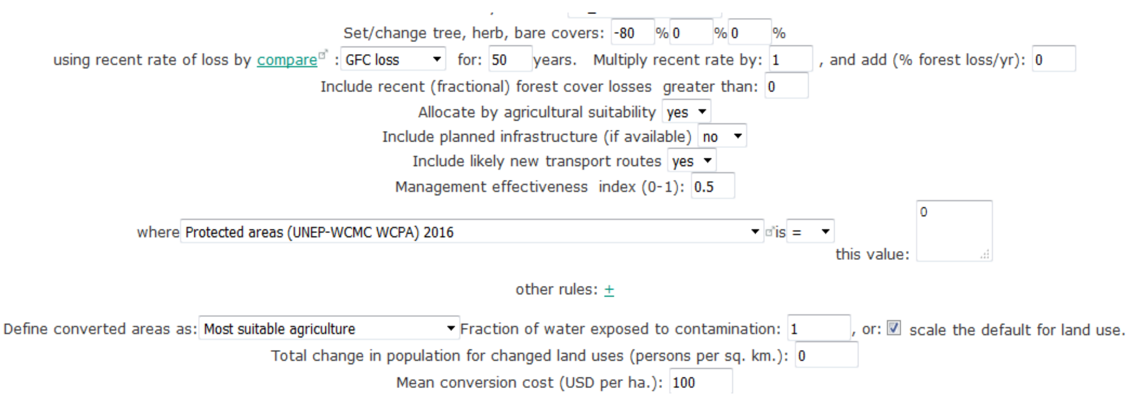

Figure 7-8: screenshot of the QUICKLUC land use model in WaterWorld. This set-up corresponds to scenario 1 in Table 6-4, below.

The example in Figure 7-8 decreases tree cover by 80%, based on agricultural suitability and includes likely new transport routes. When the ‘likely new transport routes’ option is selected, linear transport connections between the main urban centres are included in the deforestation scenario. The deforestation rates are based on data from Hansen *et al.* (2013) and continue for 50 years into the future. This leaves isolated trees. Deforestation is stopped in PAs, but this only has a management effectiveness of 0.5, which means that some deforestation in PAs may still occur. The land is converted to the most suitable of cropland or pasture.

As with most hydrological models, WaterWorld does not incorporate the climate feedback between land surface vegetation and rainfall generation. This is due to a lack of clear scientific evidence to link vegetation cover to precipitation generation (Zhang *et al.*, 2001) at the time of model development.

7.3.1.2 Integrating Changes in Climate and Management

Compound (combined land use and climate change) scenarios can also be set up and run in WaterWorld, in order to examine more complex future changes. Simulating the possible interactions between different changes is one of the major benefits of using WaterWorld (van Soesbergen and Mulligan, 2014). The LUCC scenarios developed from the management plans (described in detail in the next section) were run with additional climate changes either using the multi-model mean for the medium time horizon (2050s) for RCP8.5. The changes in land use already included in the development of the RCPs were discussed in Chapter 3, Section 3.2.2.

7.3.1.3 Developing LUCC Scenarios in WaterWorld

LUCC scenarios were developed based on the policy and management priorities discussed above. LUCC scenarios are shown in Table 7-2. The scenarios were only run using WaterWorld's annual time step so that the results are comparable with other land use and cover datasets.

Table 7-2: Key characteristics of the land use change scenarios developed for use in WaterWorld using the QUICKLUC model.

	1	2	3	4
Main change:	Decrease tree cover by 80%	Increase herb cover to 50%	Increase tree cover to 10%	Increase tree cover to 50% for all slopes of 15° or higher
Include likely new transport routes?	Yes	Yes	Yes	Yes
Base change on agricultural suitability?	Yes	Yes	Yes	No
Land converted into:	Most suitable agriculture	Most suitable agriculture	No change	No change
Management effectiveness:	0.5	0.5	0.5	0.5

The first scenario in Table 7-2 decreases tree cover by 80% over a period of 50 years, based on agricultural suitability and includes likely new transport routes. This scenario represents an increase in agricultural lands within the basin. The deforestation rates are based on data from Hansen *et al.* (2013) and continue for 50 years into the future. This leaves isolated trees. Deforestation is stopped in PAs, but this only has a management effectiveness of 0.5. This means that deforestation within PAs is possible. The land is converted to the most suitable of cropland or pasture.

The second QUICKLUC scenario increases herb cover to 50% and allocates the land changed by agricultural suitability. The land is converted to the most suitable cropland or pasture. The PAs are excluded from this change, but this only has a management effectiveness of 0.5, so some land cover change is likely to occur within PAs. Likely new transport routes are also considered.

The third scenario increases the tree cover in the area by 10%. Likely new transport routes are also considered. A medium management effectiveness (of 0.5) was chosen for all scenarios as there is evidence of deforestation still occurring within PAs in the Tana River Basin (WWF Kenya, 2018). In addition, in a global survey of PA management effectiveness, Leverington *et al.* (2008) found an average effectiveness of 0.44 across Africa. The Vision 2030 aims to increase forest cover with the country to 10%.

In the final scenario each pixel with a slope gradient of 15° or greater was reforested by 50%. Slopes with these gradients are only found in the upper Tana Basin, around the Water Towers. The Vision 2030 and Climate Change Action Plan aim to restore the Water Towers by planting trees. The Water Towers have also been shown to be important for biodiversity, with refugia existing in the mountains for most taxa, so it is important to maintain these areas.

7.3.2 ISI-MIP Agricultural Yields

The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (www.isi-mip.org, Warszawski *et al.* (2014)), and other similar intercomparison programmes, have become essential for coordinating international modelling efforts across research groups in order to better assess the impacts of climate change on agriculture and uncertainties in the modelling. The ISI-MIP project began in 2012 and was designed to look at five specific sectors, including agriculture, but to allow for a comparison across both climate models and across different impact models. ISI-MIP uses the shared socio-economic pathways (SSPs) as the basis of socio-economic input (Warszawski *et al.*, 2014). SSPs were developed to represent different levels of future socio-economic challenges for mitigation and adaptation (O'Neil *et al.*, 2014) and are also described in Table 7-5. All projections available from the ISI-MIP Fast track (FT) database use SSP2, which represents the middle of the road scenario (O'Neill *et al.*, 2014). Under the SSP2 storyline, land use change continues to be incompletely regulated in the future. Tropical deforestation continues initially, but rates decrease further into the future. Rates of increase in crop yields also decline. This occurs earliest in the more developed nations. For SSP2, international trade remains regionalised.

ISI-MIP uses global gridded crop models (GGCMs) to assess crop response to global climate change. The GGCMs included in the ISI-MIP FT database are shown in Table 7-3. EPIC, GEPIC and pDSSAT can be classified as site-based crop model, whereas LPJ-GUESS, LPJmL and PEGASUS can be classified as ecosystem models. IMAGE can be classified as an agro-ecological zone model. Ecosystem and agro-ecological zone models can be run quickly on a global scale but include less detail on crop management than site-based crop models.

The ISI-MIP database includes results on historical periods and future periods; covering the years 1960-2099. Data covering all four RCPs is accessible, although more results are available for RCP2.6 and RCP8.5. The spatial resolution of the results from ISI-MIP is 0.5° x 0.5°. The five GCMs used within ISI-MIP were chosen to represent as wide a range of global mean temperature and relative precipitation changes as possible (Rosenzweig *et al.*, 2013). However, at the time the project was developed, limited data was available in the CMIP5 archive so the GCMs chosen may not fully represent the uncertainty. The GCMs available through the ISI-MIP FT website are:

- GFDL-ESM2M (Geophysical Fluid Dynamics Laboratory, USA)
- HadGem2-ES (Hadley Centre, UK)
- IPSL-CM5A-LR (Institut Pierre Simon Laplace, France)
- MIROC-ESM-CHEM (Center for the University of Tokyo, the National Institute for Environmental Studies, and the Frontier Research Center for Global Change in Japan)
- NorESM1-M (Norwegian Climate Centre, Norway)

ISI-MIP climate input datasets were bias corrected using a statistical method (described in Hempel *et al.,* 2013). The absolute changes in temperature are not modified by the bias correction because the ISI-MIP project was designed to examine the impacts at different levels of global warming. Daily variability of the temperature data is simply adjusted to reproduce the variability of the observed data, which was provided by a 40-year average of the WATCH (Water and Global Change) project. For precipitation data, Hempel *et al.* (2013) used a multiplicative correction to adjust the monthly mean values in the historical period to the observed climatological monthly mean values.

Table 7-3: Agricultural impact models participating in the ISIMIP project available from the FT database

Model		**Institution**	**References**
Environmental Policy Integrated Climate model	EPIC	BOKU; University of Natural Resources and Life Sciences, Vienna	Kiniry *et al.*, 2011; Izaurralde *et al.*, 2005
Geographic Information System-based Environmental Policy Integrated Climate model	GEPIC	EAWAG, Swiss Federal Institute of Aquatic Science and Technology	Liu *et al.*, 2007; Williams, 1989; Izaurralde *et al.*, 2005; Folberth *et al.*, 2012
Global AgroEcological Zone model in the Integrated Model to Assess the Global Environment	IMAGE	Netherland Environmental Assessment Agency (PBL)	Bouwman *et al.*, 2006
Lund-Potsdam-Jena managed Land dynamic global vegetation and water balance model	LPJmL	Potsdam Institute for Climate Impact Research	Bondeau *et al.*, 2007
Lund-Potsdam-Jena General Ecosystem Simulator	LPJ-GUESS	Lund University, department for Physical Geography and Ecosystem Science, IMK-IFU, Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany	Bondeau *et al.*, 2007; Lindeskog *et al.*, 2013
Parallel Decision Support System for Agro-technology Transfer	pDSSAT	University of Chicago, Computation Institute	Elliott *et al.*, 2013; Morgan *et al.*, 2003
Predicting Ecosystem Goods And Services Using Scenarios model	PEGASUS	Tyndall Centre for Climate Change Research, University of East Anglia, UK; McGill University, Canada	Deryng *et al.*, 2011; 2014

Details of the GGCMs used in the ISI-MIP database and key differences between the crop models are presented in Rosenzweig *et al.* (2014) and are shown in Table AVI-1 in the Appendices. All GGCMs included in the ISI-MIP database take into account water stress and temperature. There are also options to include CO_2 forcing and irrigation forcing. Two irrigation scenarios are considered in the ISI-

MIP FT project: no irrigation (i.e. rain-fed agriculture) and full irrigation (which assumes water is available to fully irrigate the crops). The two CO_2 scenarios are CO_2 fertilisation and no CO_2 fertilisation. It is widely known that crops can benefit from CO_2 fertilisation, but the specific effects are still uncertain. Higher CO_2 increases the rate of photosynthesis. For the 'no CO_2' experiments, a baseline level of CO_2 was included in the model. The baseline level and corresponding year for each GGCM is shown in Table AVI-1. Each GGCM includes different elevated CO_2 effects. To simulate elevated CO_2 effects, EPIC, GEPIC and PEGASUS include radiation use efficiency and transpiration efficiency. IMAGE and pDSSAT also consider radiation use efficiency. LPJ-GUESS and LPJmL include leaf-level photosynthesis and stomatal conductance. These differences are also shown in Table AVI-1. All GGCMs apart from LPJ-GUESS were included in this analysis. Although changes to fertilizer use are considered in some later ISI-MIP simulations, nitrogen fertilizer scenarios were not available through the ISI-MIP FT.

Maize, wheat, sorghum, millet and sugarcane have been examined in this research. As previously shown, maize is the top crop in the country in terms of area harvested and sugarcane is the top crop in terms of yield. Sorghum, wheat and millet are also in the top 10 crops in terms of area harvested, as shown earlier in Table 6-1 (FAOSTAT, 2014). Data was obtained from the ISI-MIP FT data portal (available at: https://esg.pik-potsdam.de/search/isimip-ft/). The GGCMs included in the database were all run at 0.5 x 0.5° spatial resolution. The crop yield (measured in tonnes per hectare per year) was the only variable examined in this research.

Table 7-4 shows the number of scenarios available for each crop, per GCM. Not all these scenarios were used. The scenarios only available for HadGem2-ES were not included, as they could not be compared to the results from other GCMs. Furthermore, only results from RCP2.6 and RCP8.5 were included in this investigation because there are not as many results for the other RCPs, so the full range of results cannot be analysed.

Table 7-4: Number of scenarios available for future yields.

GCM	Maize	Wheat	Sorghum	Millet	Sugarcane
GFDL ESM 2M	60	60	8	24	24
HadGem 2ES	90	90	20	36	36
IPSL CM5A LR	60	60	8	24	24
MIROC ESM CHEM	60	60	8	24	24
NorESM1 M	60	60	8	24	24

The differences in the number of available scenarios largely comes from the number of GGCMs run for each crop. For sorghum, only two GGCMs are available (EPIC and IMAGE). For millet and sugarcane, three GGCMs (EPIC, IMAGE and LPJmL) are available, and for wheat and maize all seven of the GGCMs are available. Table 7-5 shows the number of scenarios considered for each GGCM and each crop for each of RCP2.6 and RCP8.5. LPJ-GUESS was not included in this analysis because, unlike the other GGCMs, it simulates potential yields which are not limited by management or nutrient constraints (Blanc, 2017).

Table 7-5: Number of scenarios used in this analysis for each crop and each GGCM

	Maize		Wheat		Sorghum		Millet		Sugarcane	
	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
EPIC	10	10	10	10	10	10	10	10	10	10
GEPIC	10	10	10	10	-		-		-	
IMAGE	10	10	10	10	10	10	10	10	10	10
LPJML	40	40	40	40	-		20	20	10	10
PDSSAT	40	40	40	40	-		-		-	
PEGASUS	28	28	28	28	-		-		-	

For this analysis, the medium time horizon corresponding to the 2050s that has been examined in previous chapters was determined. The mean of the period 2041-2060 was extracted from the data and compared to the historical yields. The difference between the historical and future periods was calculated for each cell in the basin. The results were then reclassified to show areas where yields were increasing or decreasing for each model. These reclassified results were added together to determine the agreement between the models (i.e. the number of models projecting an increase in crop yield per cell).

7.3.2.2 Wallace Initiative for Agricultural and Used Species

In addition to ISI-MIP crop yield data, the Wallace Initiative database (described in detail in Chapter 6, Section 6.3.3) was used to examine changes in 'used' species. These are species that are important to the population, socially and economically. Table 7-6 provides a list of the species considered, as well as their importance. Some species listed are considered because of their agricultural importance either nationally or specifically within the Tana River Basin.

Other species were included in the list of agroforestry or suitable tree planting species by the Kenya Forestry Research Institute (KEFRI). KEFRI (1990) splits the afforestation species by the ecozone that they are best suited for. Ecozones are split by the volume of rainfall they receive annually: Ecozone II (over 1400 mm); Ecozone III (800 to 1400 mm); Ecozone IV (400 to 800 mm) and Ecozones V and VI (less than 400 mm). Due to the size and heterogeneity of the basin, all ecozones are relevant for this research. All of the tree species listed by KEFRI that were available in the Wallace Initiative database and present in the Tana River Basin were examined. Of the 13 agroforestry species listed, 9 were available in the database and present in the basin. In addition, 20 afforestation species have been analysed here. *Ficus sycomoros* and *Phoenix reclinata* were also identified as useful afforestation species. These plants were analysed in Chapter 6, Section 6.4 because of their importance as food sources for the endemic primates but showed little change in suitable climate space with higher temperatures.

Some afforestation species are important for charcoal production. Charcoal production in the rangelands is an important income generation option and is done by most households on a small-scale basis. It also provides an important financial activity in the dry seasons and during droughts. Charcoal in the ASALs is frequently produced from various acacia species (Kituyi *et al.*, 2001). It is illegal to cut down endangered native trees for fuelwood, so these fast-growing species are often grown for that purpose. Farmland trees are also planted to provide shade and act as wind breaks. Fruit trees such as mango (*Mangifera indica*) and avocado (*Persea Americana*) are commonly planted and can provide extra income (Kituyi *et al.*, 2001). These fruit trees can also be used for charcoal production if they are the most readily available. Beans are an important crop in Kenya. However, details of the specific species grown in the region are not included in the FAO Database. Here, the common bean (*Phaseolus vulgaris*) was used to represent the different types of bean grown in the basin.

Table 7-6: Used Species from Wallace Initiative Database, v.3

Scientific Name	**Importance/use**
Acacia tortilis	Agro-forestry species
Casuarina equisetifolia	Agro-forestry species
Cordia africana	Agro-forestry species
Gliricidia sepium	Agro-forestry species
Leucaena leucocephala	Agro-forestry species
Markhamia lutea	Agro-forestry species
Sesbania sesban	Agro-forestry species
Tamarindus indica	Agro-forestry species
Common bean *Phaseolus vulgaris*	Beans are a top crop (FAO)
Robusta coffee *Coffea canephora*	Coffee is an important crop in Upper Tana
Arabica coffee *Coffea Arabica*	Coffee is an important crop in Upper Tana
Papaya *Carica papaya*	Cultivated as a tropical fruit
Pineapple *Ananas comosus*	Grown in lower Tana (Luke *et al.*, 2005)
Mango *Mangifera indica*	Grown in lower Tana (Luke *et al.*, 2005)
Tea *Camellia sinensis*	Tea plantations in Upper Tana
Cowpea *Vigna unguiculata*	Top crop (FAO)
Avocado *Persea americana*	Top crop (FAO)
Tomato *Solanum lycopersicum*	Top crop (FAO)
Pigeonpea *Cajanus cajan*	Top crop (FAO)
Acacia senegal	Tree planting
Azadirachta indica	Tree planting
Terminalia brownii	Tree planting
Brachystegia spiciformis	Tree planting
Acacia seyal	Tree planting
Balanites aegyptiacus	Tree planting
Cordia sinensis	Tree planting
Salvadora persica	Tree planting
Borassus aethiopum	Tree planting
Syzygium cumini	Tree planting
Acacia xanthophloea	Tree planting
Syzygium jambos	Tree planting

Table 7-8

Maesopsis eminii	Tree planting
Acacia mearnsii	Tree planting
Ocotea usambarensis	Tree planting
Brachylaena huillensis	Tree planting
Cupressus lusitanica	Tree planting
Pinus patula	Tree planting
Schinus molle	Tree planting
Dalbergia melanoxylon	Tree planting

The changes in the distribution of these plants within their climate space with different levels of warming (namely 1.5 °C, 2°C, 2.7°C, 3.2°C and 4.5°C above pre-Industrial) was analysed. The reasons behind these temperature increments are discussed in Chapter 5, Section 3.3. Due to the long time periods necessary for most plants to move, only the ‘no dispersal’ scenario was considered for these used species.

7.3.3 The Importance of Soil Properties for Agricultural Development

Soils are extremely important parts of ecosystems as they store water and nutrients which enable plant growth. A soil’s physical and chemical properties, and changes to them, have profound consequences for agriculture. Important soil properties for agricultural land include the soil water-holding capacity, infiltration rate, organic matter content and nutrient availability. Degradation of soil properties is often irreversible, as soils are finite resources. Davis (2016) notes that soil types play a significant role in the resilience of vegetation in dryland environments.

Soil information was downloaded from the Global Agro-Ecological Zones (GAEZ) website. GAEZ uses the Harmonised World Soil Database developed by the Land Use Change ad Agriculture Program of IIASA and the FAO. The soil information included in the Harmonised World Soil Database is processed. The GAEZ soil data, such as soil nutrient availability and retention capacity, were estimated on a crop by crop basis and given a specific suitability rating (IIASA/FAO, 2012). Soil properties will constrain the area suitable for agricultural production so should be considered alongside other changes to crop suitability with climate change. Nutrient availability and soil workability can influence agricultural suitability and quality of the land.

7.3.4 Land Use Harmonisation v2 (LUH2)

Land Use Harmonisation Version 2 (LUH2) is a coordinated land use dataset using the official CMIP6 future scenarios (Hurtt *et al.*, In prep). It is being developed as part of the Land-Use Model Intercomparison Project (LUMIP). It covers the period 2015-2100, as well as including historical data for the period 850-2015. The data has a spatial resolution of 0.25 by 0.25°. The fractions of land use states, transitions between these states and management are included.

LUH2 scenarios involve different shared socio-economic pathways (SSPs), which are described in Table 7-7. SPP1 assumes low challenges for mitigation and adaptation. SSP2 is not included in the LUH2 scenarios used here but was used in the ISI-MIP data described above. SSP3 assumes high challenges for mitigation and adaptation, including regionalised policies and slow development. SSP4 also assumes high challenges for adaptation, but low challenges for mitigation. SSP5 shows the reverse: low challenges for adaptation but high for mitigation.

Table 7-7: Storylines in the SSPs. Adapted from (O'Neill et al., 2017)

SSP	Description
SSP1 Sustainability	Land use is strongly regulated. Deforestation rates are greatly reduced. Crop yields are rapidly increasing. Low challenges to mitigation and adaptation.
SSP2 Continuation	Land use change is incompletely regulated. Deforestation continues. Rates of crop yield increases decline over time. Medium challenges to mitigation and adaptation.
SSP3 Fragmentation	Land use change is barely regulated. Deforestation continues. Rates of crop yield increases decline over time. High challenges to mitigation and adaptation.
SSP4 Inequality	Land use is strongly regulated in high income countries, but deforestation continues in lower income countries. Low challenges to mitigation, high challenges to adaptation.
SSP5 Conventional (Fossil Fuel) Development	Land use change is incompletely regulated. Crop yields are rapidly increasing. High challenges to mitigation, low challenges to adaptation.

The different SSP implemented in each integrated assessment model (IAM) is shown in Table 7-8.

Table 7-8: Characteristics of the scenarios in LUH2

SSP	RCP	IAM
1	2.6	IMAGE
4	3.4	GCAM
4	6.0	GCAM
3	7.0	AIM
5	8.5	REMIND-MAGPIE

Land use states are the fractions of each grid cell used by the different land uses. There are 14 different land uses covered: two pasture land use types, five crop types and forested and non-forested, primary and secondary land. For these datasets, primary land is defined as natural vegetation that has never been impacted by human activities. The five crop types are C3 annual, C3 perennial, C4 annual, C4 perennial and C3 nitrogen-fixing crops. C3 crops are cool season plants, whereas C4 are warm season plants. Examples of annual C3 and C4 crops would be wheat and corn respectively.

For this research, the mean of the 20-year period centring on the 2050s (2041-2060) has been extracted for each land use state to compare with the most recent historical values (which are from the year 2005). The five crop types were combined to provide a total cropland figure, as were the two pasture land use states to give a general overview of projected changes in croplands and pasture.

7.4 Results

The results of individual land use and agricultural analyses are presented before results from the different sectors are combined using GIS.

7.4.1 WaterWorld QUICKLUC and Combined Scenarios

These scenarios were run in order to provide an indication of the relative importance of changes in water balance caused by land use change or climate change. Figure 7-9 shows the percentage change in water balance with the QUICKLUC scenarios. Percentage changes in water balance are minor when LUC alone is considered. Reducing the tree cover and increasing the herb cover both lead to small increases in the basin-average water balance. By contrast, increasing the tree cover leads to a small reduction in water balance. The compound scenarios show significantly greater changes in the basin-average water balance change for all scenarios.

In all cases, the effects of climate change are much more significant than the effects of land cover change. The percentage changes for the compound scenarios (land use and climate change combined) lie in between.

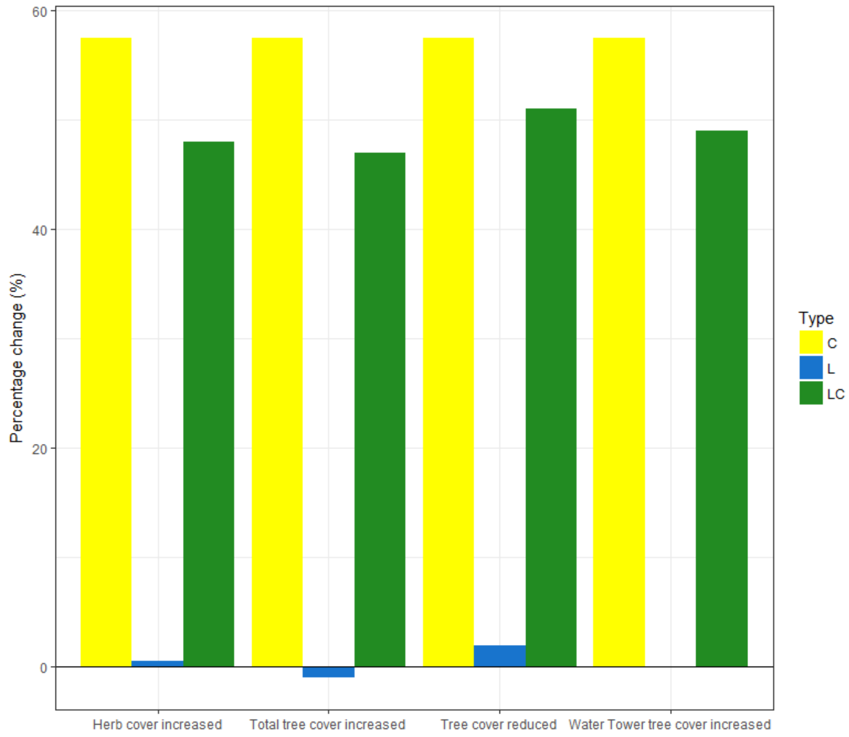

Figure 7-9: Basin-average percentage change in water balance for each of the 4 QUICKLUC scenarios (shown on the x-axis) by the 2050s. Yellow bars show the effects of climate change only, blue bars show the effects of land use change only and the green bars show the effects of compound scenarios (land use and climate change combined). The climate change scenario used here is the multi-model mean for RCP8.5.

The variation in change to water balance across the basin is considerable. Figure 7-10 shows the average changes within the administrative areas of the basin for the climate, land use change and compound scenarios. The greatest changes occur in some districts within the upland area in the northwest of the basin, particularly Machakos, Embu and Tharaka-Nithi counties. Smaller changes are seen in the counties with significantly higher and lower elevations, such as Nyeri and Garissa respectively. As seen with the basin-average values in Figure 7-9, the climate change scenario leads to greater changes than the land use change scenarios in most counties. One county which does not show the same pattern is Lamu, which is located in the southeast of the basin. Here, the ensemble mean climate change scenario is projected to lead to minor reductions in average annual water balance, whereas the land use change scenarios increasing herb cover and reducing tree cover lead to increases in average water balance.

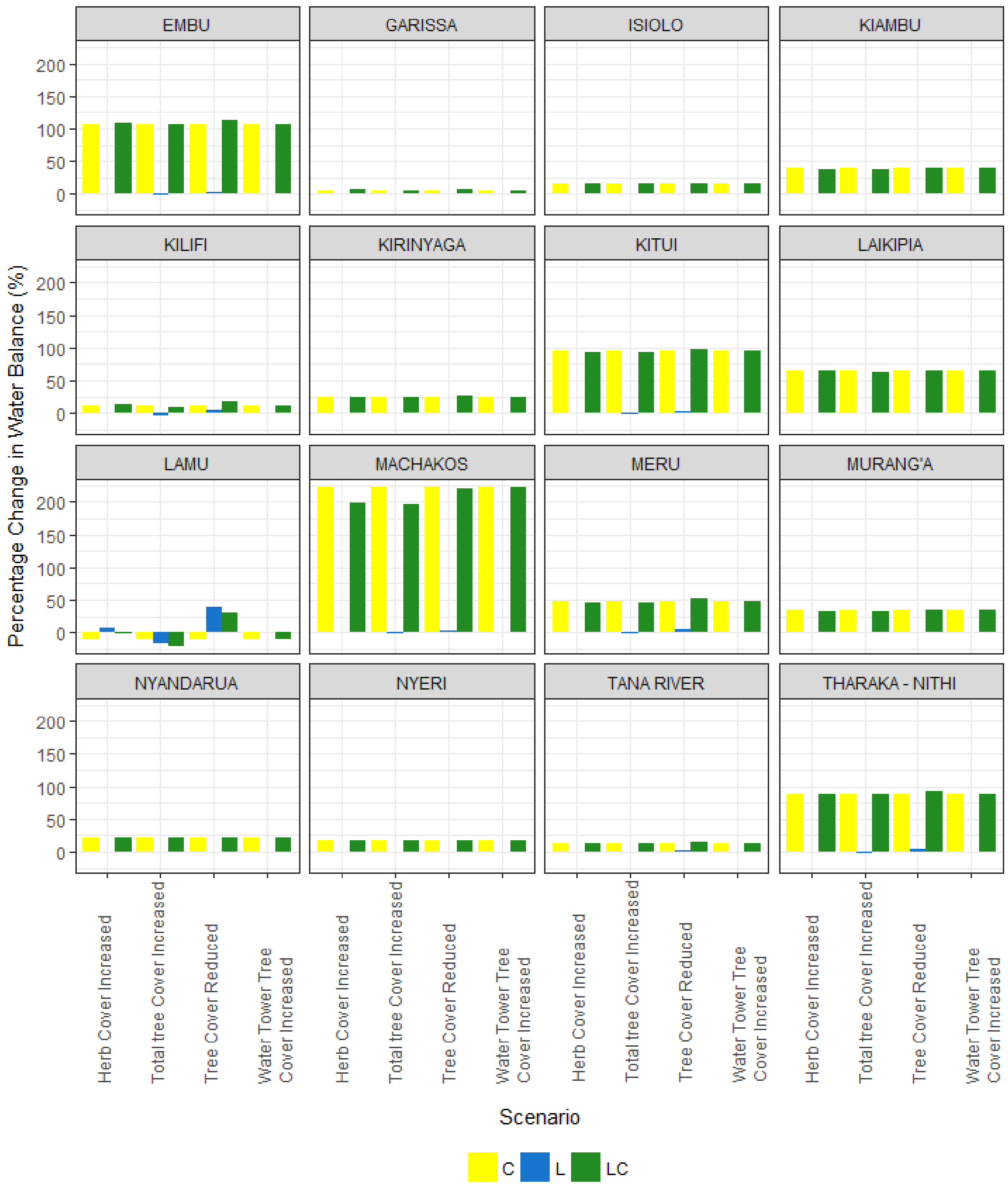

Figure 7-10: Average percentage change in water balance for each administrative region by the 2050s. The x-axis shows the QUICKLUC scenario. Each panel shows a different administrative area/district. Yellow bars show the effects of climate change only, blue bars show the effects of land use change only and the green bars show the effects of compound scenarios (land use and climate change combined). The climate change scenario used here is the multi-model mean for RCP8.5.

7.4.2 Changes to Major Crop Yields

This section examines changes to the five major crops from the ISI-MIP database.

7.4.2.1 Millet

Millet is grown throughout the Tana River Basin, with the highest yields in the northern area. Climate change is expected to alter millet yields. Figure 7-11 shows the sum of change in millet yield across the whole river basin, with CO_2 effects included for RCP2.6 by the 2050s. The graph shows the difference between each scenario, as well as the difference between no irrigation and full irrigation conditions. Significantly differences in projections are seen for the five GCMs used within the EPIC GGCM, with two GCMs (HadGem2-ES and IPSL-CM5A-LR) projecting decrease in total millet yield in the future. More agreement between the GCMs is seen in the results from IMAGE and LPJML. The millet yield changes projected by LPJML are minor in comparison to the other two crop models presented here. However, these results still show a disagreement in the sign of yield change between the five GCMs. Generally, there is an agreement on the sign of yield change between the irrigation and no irrigation scenarios for the same model.

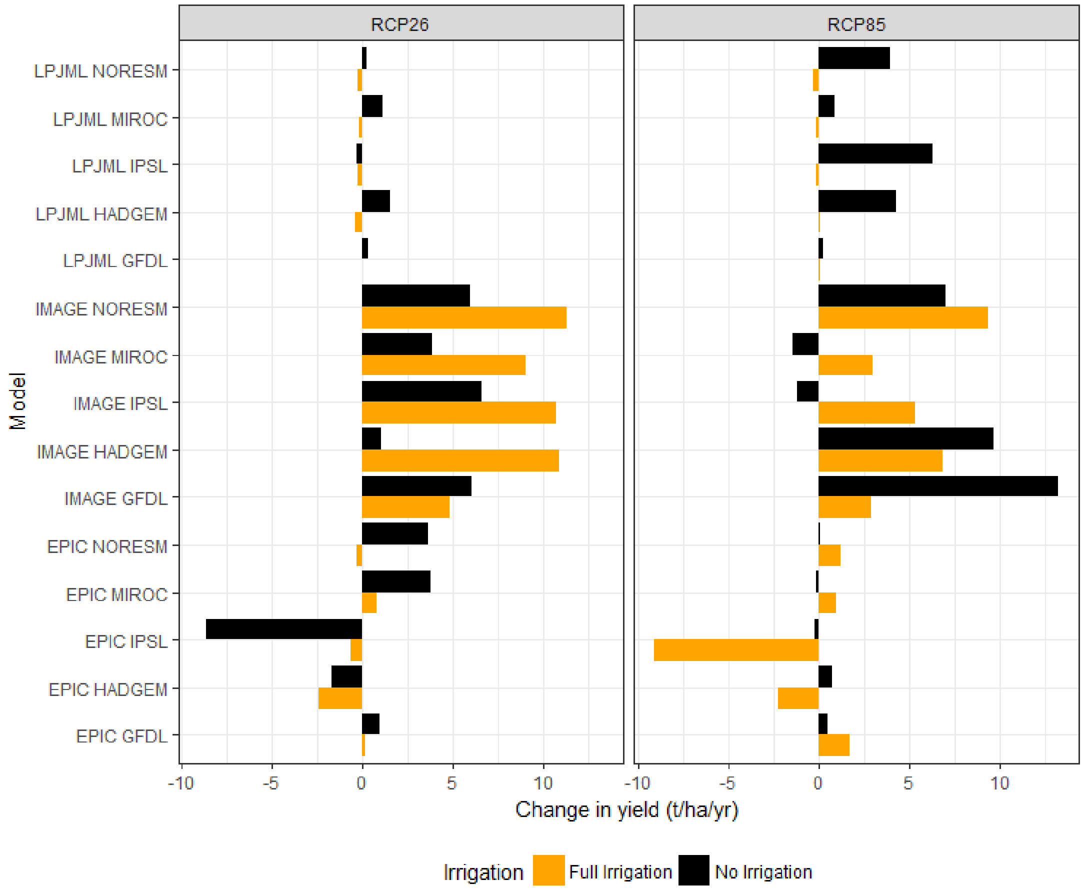

Figure 7-11: Sum of change in millet yield within the Tana River Basin with CO_2 effects for RCP2.6 and RCP8.5, with no irrigation (black) and full irrigation (orange)

A similar pattern of change is seen for RCP8.5. The increases in total millet yield within the basin with no irrigation are greater than those seen under RCP2.6 conditions. Differences between the sign of change in millet yield between the no irrigation and full irrigation conditions are seen in some cases, for example IMAGE MIROC-ESM-CHEM and IMAGE IPSL-CM5A-LR. Overall, these results suggest that, with CO_2 effects included, total millet yields could increase within the basin. However, the models do not agree as to where these increases are likely to occur.

Figure 7-12 shows the number of simulations resulting in an increase in millet yield, for RCP2.6 and RCP8.5 with CO_2 effects, comparing full irrigation and no irrigation. Yield increases are projected by all GCMs and GGCMs for the two cells in the northwest of the basin under RCP2.6 and RCP8.5 scenarios with CO_2 effects, with and without irrigation. Scenarios with no irrigation included create more variation between the results from the individual GCMs and GGCMs.

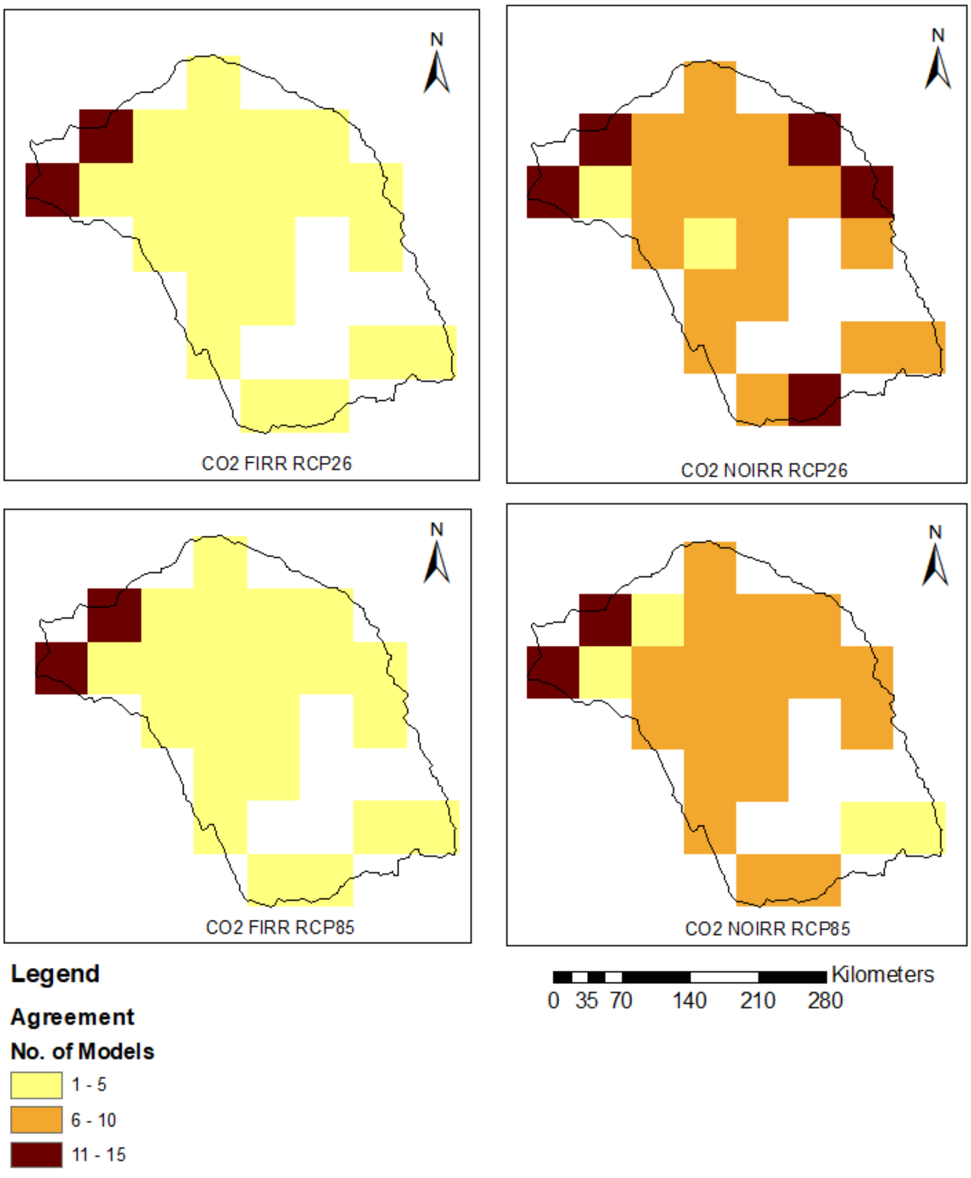

Figure 7-12: Number of simulations resulting in an increase in millet yield. The total possible number of models agreeing is 15. FIRR refers to full irrigation and NOIRR refers to no irrigation.

Excluding CO_2 effects causes the changes in yield to become much smaller. Results without CO_2 effects are only available for the LPJML GGCM, so cannot show the full range of possible changes. This is shown in Figure 7-13. Generally, excluding CO_2 effects leads to a small decrease in total millet yield for the Tana River Basin as a whole. Only MIROC-ESM-CHEM projects a minor increase in yield. The spread between the different GCMs for the LPJML crop model can be seen in Figure 7-14. With full irrigation, the two CO_2 scenarios are fairly similar in magnitude and spread for both RCPs. However, without irrigation, the difference between the five GCMs is greater when CO_2 fertilization is included, demonstrating uncertainty as a result of CO_2 effects.

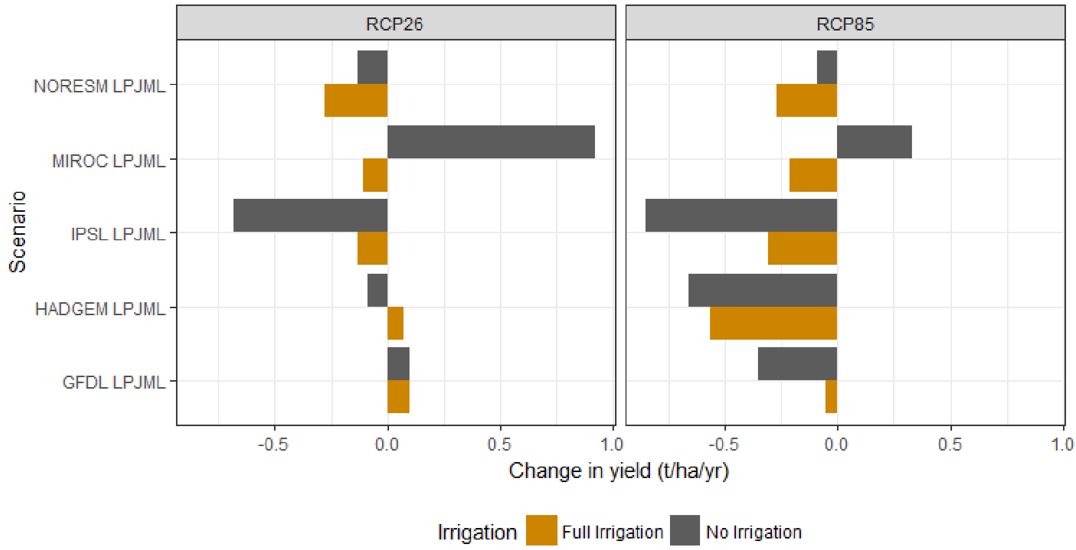

Figure 7-13: Changes to millet yields within the Tana River Basin without CO_2 effects included. This was only available for the LPJML GGCM

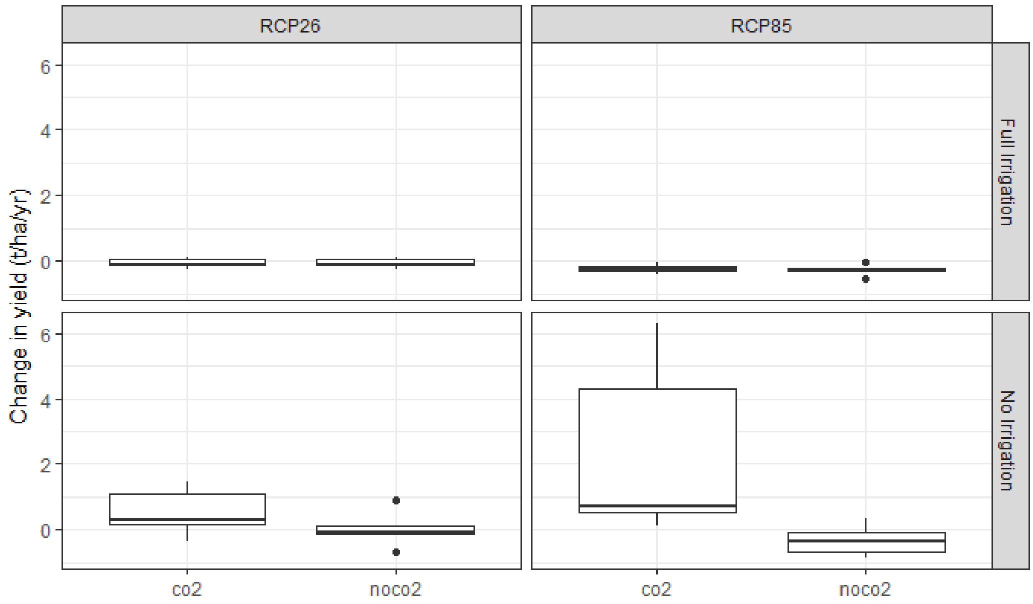

Figure 7-14: Spread of results with and without CO_2, for 2 RCPs and irrigation scenarios for millet using the LPJML GGCM.

7.4.2.2 Maize

Maize is a very important crop in Kenya and is grown across the Tana River Basin. More model results are available for maize than have been presented for millet, so a greater range of possible changes have been analysed. Figure 7-15 shows the total change in maize yield within the Tana River Basin with CO_2 effects for RCP8.5 conditions, for both full irrigation and no irrigation included. The differences between the GGCMs can be easily seen. PEGASUS projects decreases in total maize yields for every scenario. PDSSAT and LPJML show increases in yield with no irrigation, but decreases with full irrigation. EPIC and GEPIC show a variation in the sign of yield change between the different GCMs and irrigation scenarios.

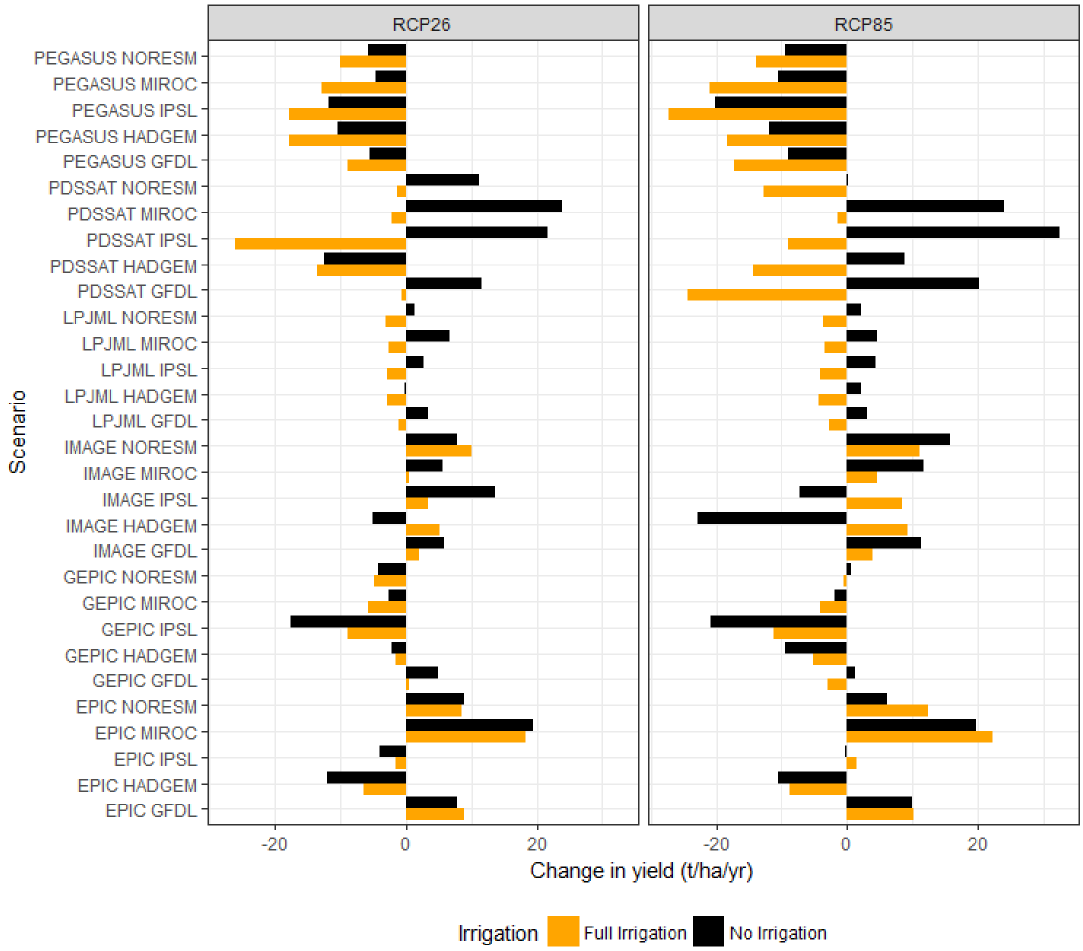

Figure 7-15: Sum of change in maize yield within the Tana River Basin with CO_2 effects for RCP2.6 and RCP8.5, with no irrigation (black) and full irrigation (orange).

When CO_2 effects are not taken into account, nearly all total maize yields decrease with both full irrigation and no irrigation (Figure 7-16). It should be remembered that there are not as many sets of results for scenarios without CO_2 included, so the full range of possible changes cannot be examined.

Figure 7-17 shows the spread of model results with and without CO_2 effects and irrigation for the 2 RCPs. The greatest spread is seen for the scenarios where CO_2 effects are included but irrigation is not.

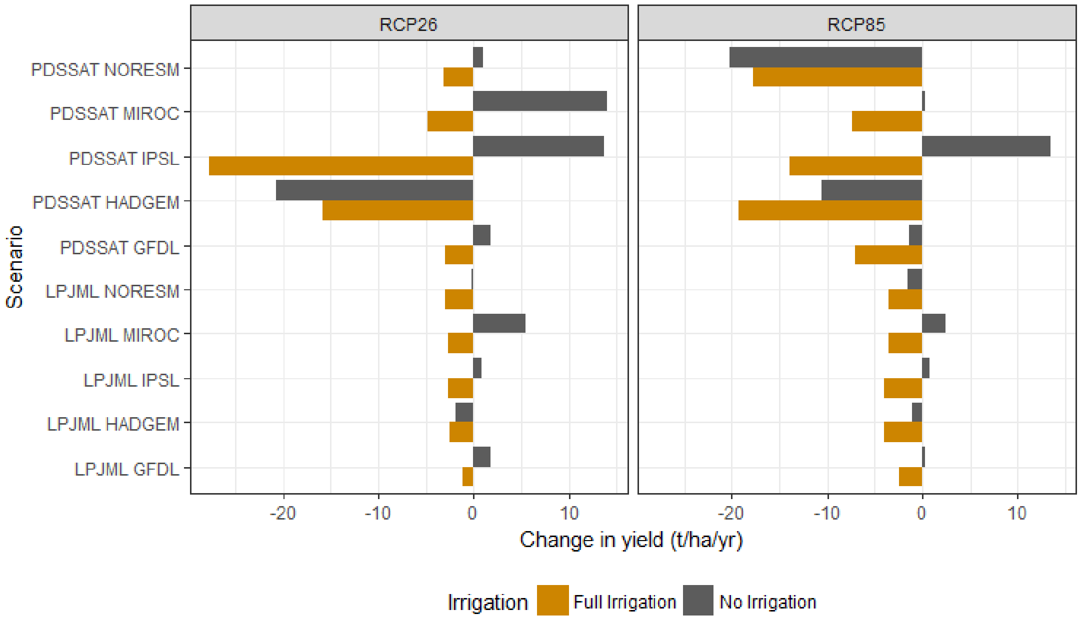

Figure 7-16: Sum of change in maize yield within the Tana River Basin without CO_2 effects for RCP8.5, with no irrigation (grey) and full irrigation (yellow)

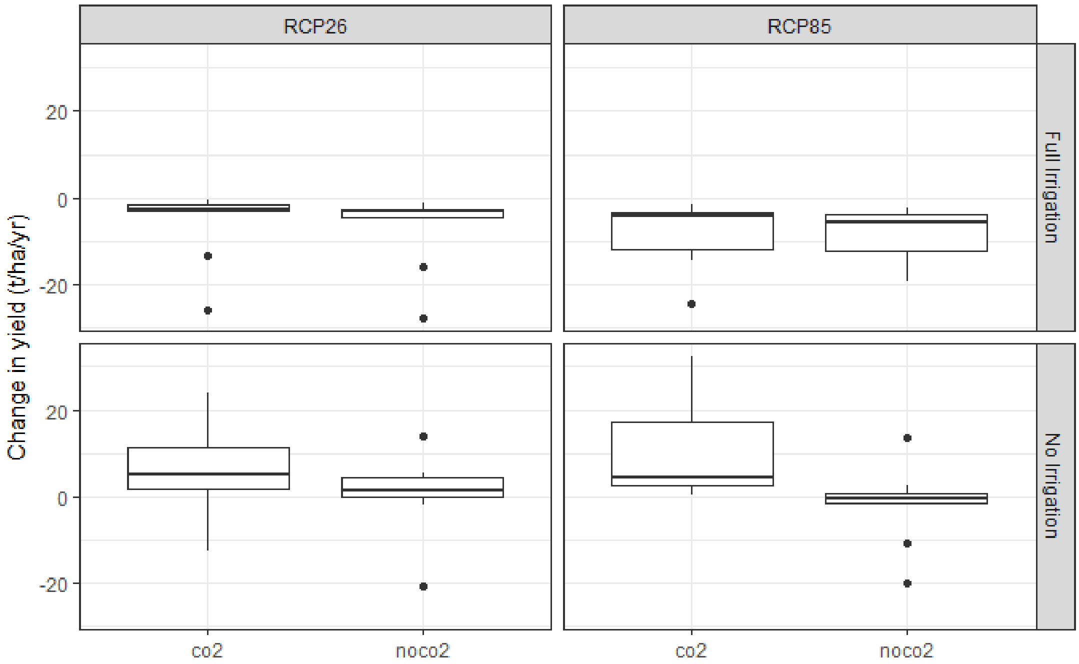

Figure 7-17: Spread of results with and without CO_2, for 2 RCPs and irrigation scenarios for change in total maize yield within the Tana River Basin

Figure 7-18 shows the spatial pattern in the number of simulations resulting in increased maize yields. Yield increase projected by some models across the north of the basin, under CO_2 fertilisation scenarios. There is greater agreement for the no irrigation scenarios. More increases are seen with no irrigation because the changes in climate are thought to provide enough water, making further irrigation unnecessary. The increases in potential yield are slightly more pronounced for RCP2.6 conditions than RCP8.5. There are no cells in the basin where all 30 of the models project increases in yields.

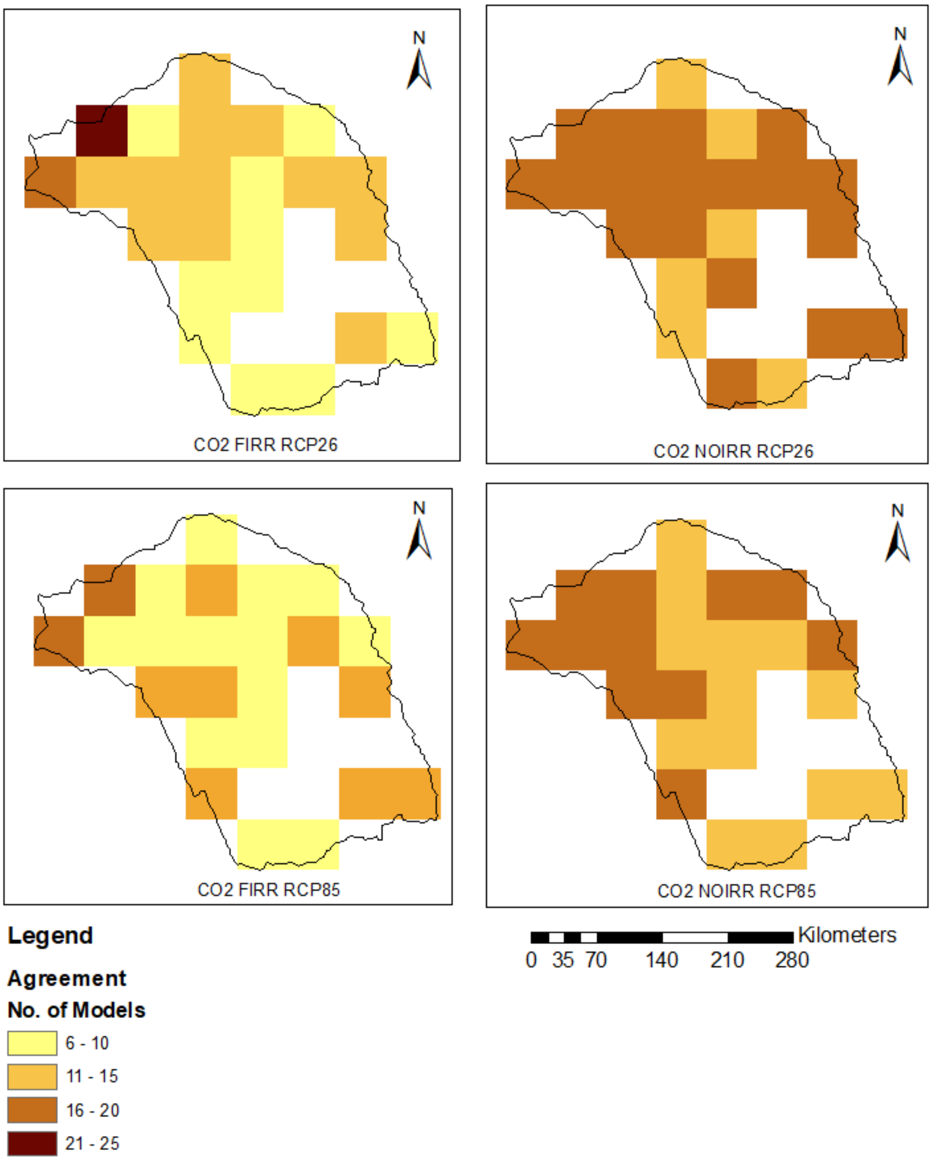

Figure 7-18: Number of simulations resulting in increased maize yields. The total possible number of models agreeing is 30.

7.4.2.3 Wheat

Over half of the scenarios shown in Figure 7-19 show decreases in total wheat yields with both full irrigation and no irrigation for RCP2.6. Generally, full irrigation scenarios lead to greater reductions in wheat yield than no irrigation scenarios, particularly for the EPIC, GEPIC and PDSSAT models. LPJML and IMAGE largely project increases in total wheat yield. The same is true for RCP8.5, but some differences in yield are larger for this high end climate scenario. The IMAGE and LPJML models project increases in net wheat yield across the basin for the majority of GCMs.

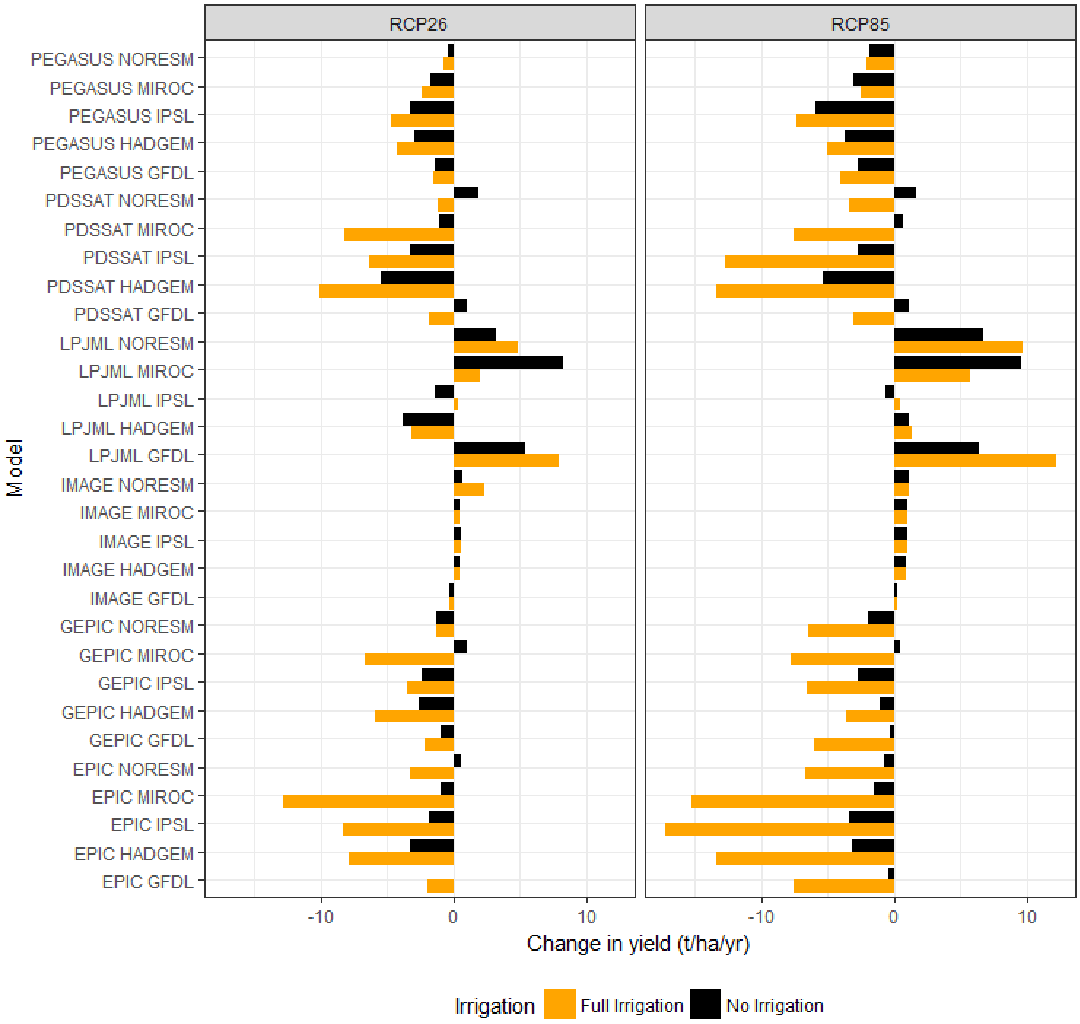

Figure 7-19: Sum of change in wheat yield within the Tana River Basin with CO_2 effects for RCP2.6 and RCP8.5

Figure 7-20 shows the change in total wheat yield without CO_2 effects included. There are fewer scenarios available but all models project decreases in total wheat yield across the basin. Generally, the decreases are more substantial with full irrigation than with no irrigation. Figure 7-21 shows the spread of results. Generally, the negative change in yield is greater without CO_2 included, both with and without irrigation included.

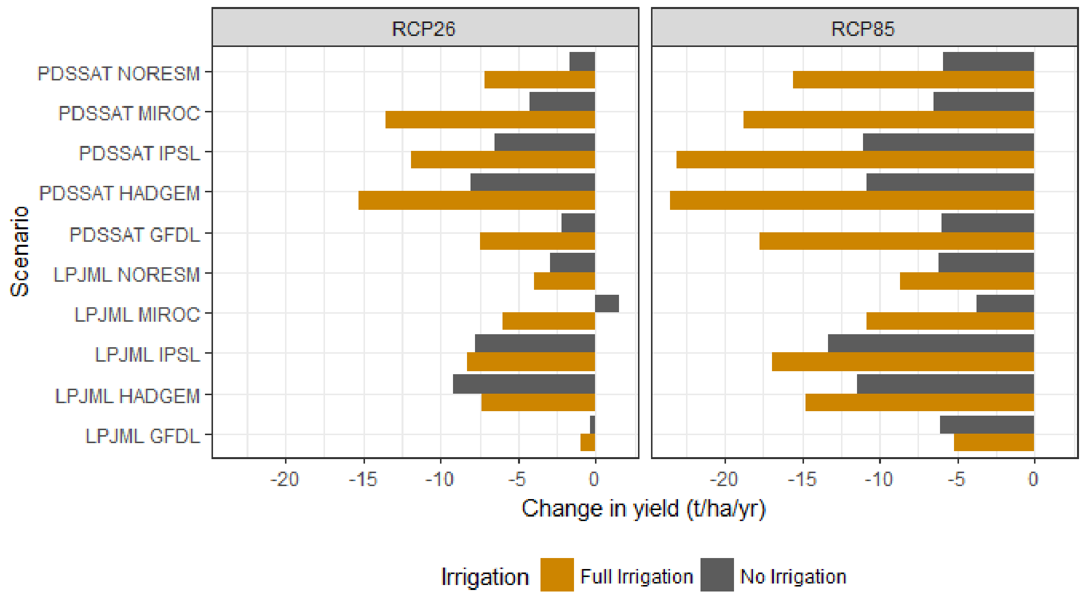

Figure 7-20: Sum of change in wheat yield within the Tana River Basin without CO_2 effects for RCP2.6 and RCP8.5

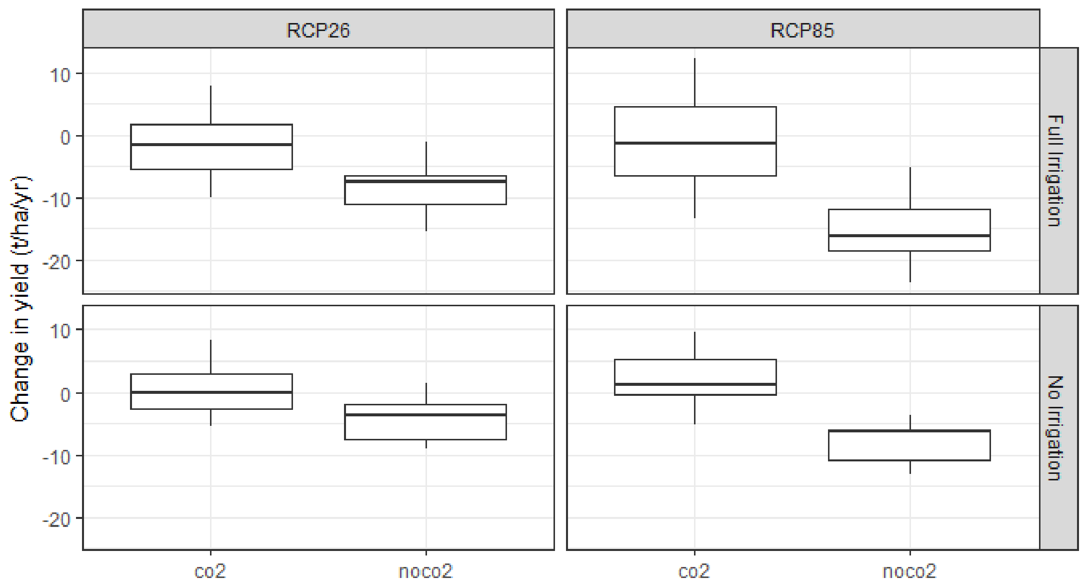

Figure 7-21: Spread of results with and without CO_2, for 2 RCPs and irrigation scenarios for change in total wheat yield within the Tana River Basin.

The spatial changes to wheat yield are similar to those seen with maize in terms of where the majority of models agree (Figure 7-22). There are no cells in the basin where all of the models project increases in yields, but there are cells in the north of the basin which could experience increases in wheat yields in the majority of cases. The differences between RCP2.6 (top) and RCP8.5 (bottom row) are not substantial. More models project increases in yields across the basin with no additional irrigation than with full irrigation.

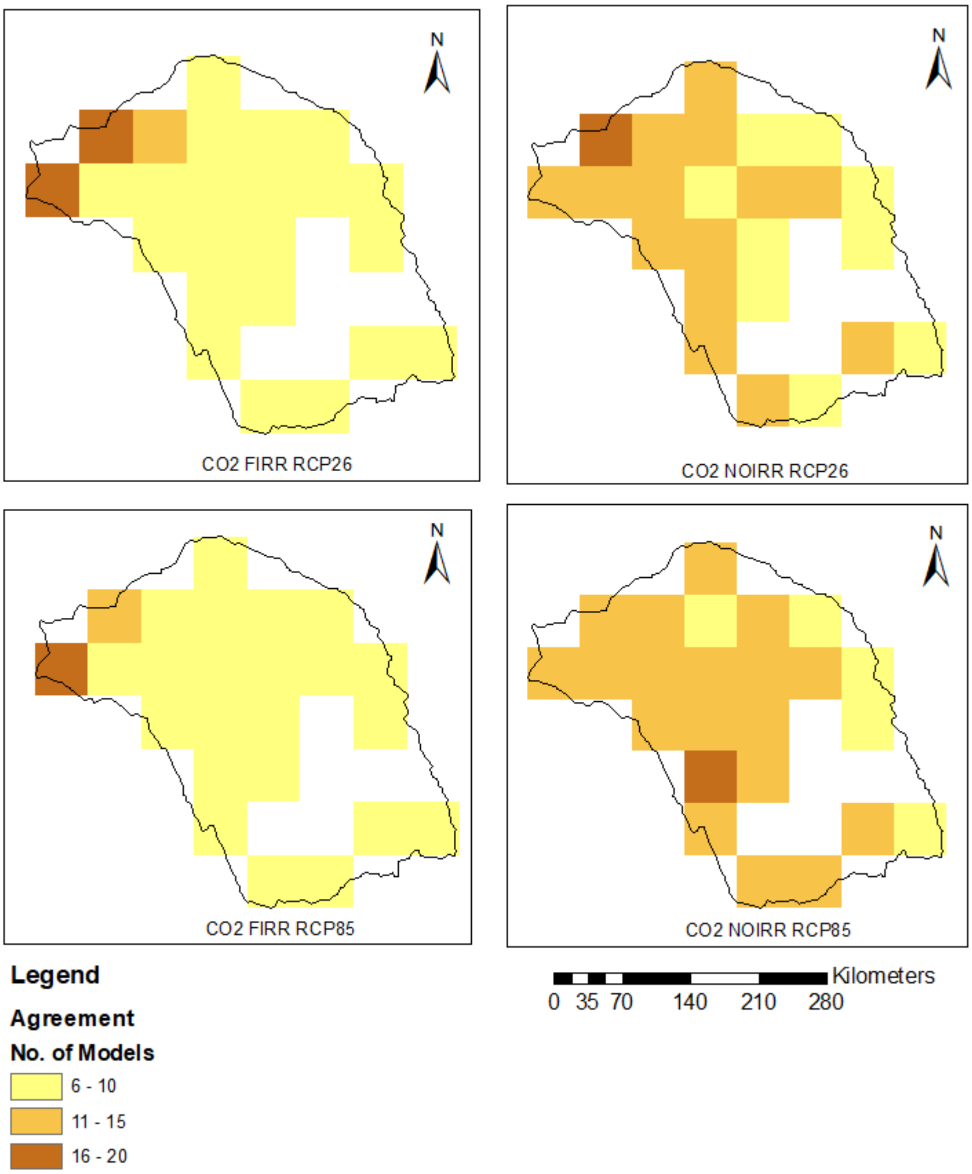

Figure 7-22: Number of simulations resulting in an increase in wheat yields. The total number of possible models agreeing is 30.

7.4.2.4 Sorghum

Figure 7-23 shows that the majority of scenarios project an increase in total sorghum yield for RCP2.6 conditions with no irrigation included. By contrast, the two GGCMs disagree on the sign of the yield change assuming full irrigation. EPIC results project reductions in total yield, whereas IMAGE predicts increases. This pattern is not as clear for RCP8.5. Scenarios with no CO_2 effects were not considered for sorghum as only four projections without CO_2 fertilisation effects were included in the ISI-MIP FT database.

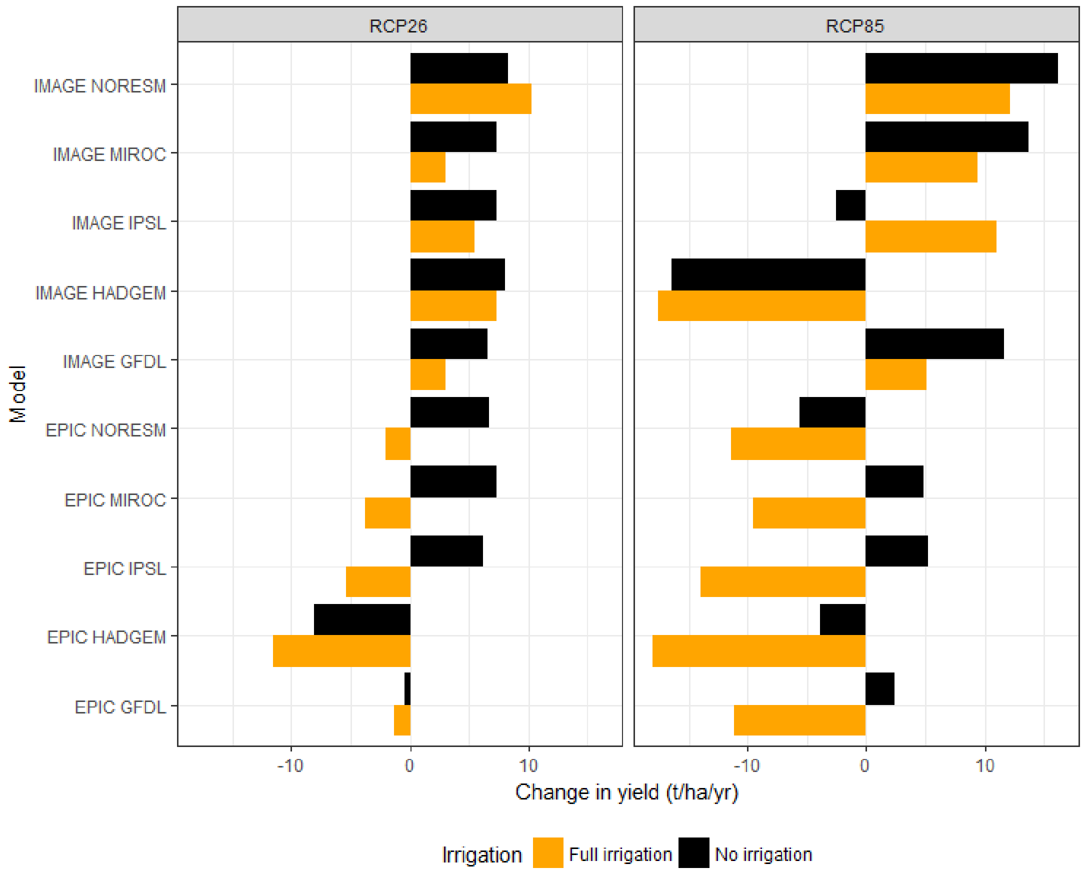

Figure 7-23: Sum of change in sorghum yield within the Tana River Basin with CO_2 effects for RCP2.6 and RCP8.5

Figure 7-24 shows the number of simulations resulting in an increase in sorghum yield. There are two cells in the north of the basin where most models agree that sorghum yields could increase with CO_2 effects and full irrigation. Large areas of the basin could see yield increases with CO_2 and no irrigation, suggesting that additional irrigation is not necessary in the future climate. As shown with the other crops, the spatial pattern of change is similar for RCP2.6 and RCP8.5.

The spread of model results for sorghum is shown in Figure 7-25. The variation between the models is greater for RCP8.5 both with full irrigation and with no irrigation included, with some models projecting increases in total sorghum yield and others projecting reductions. The range of model results is particularly narrow for RCP2.6 when no irrigation is included.

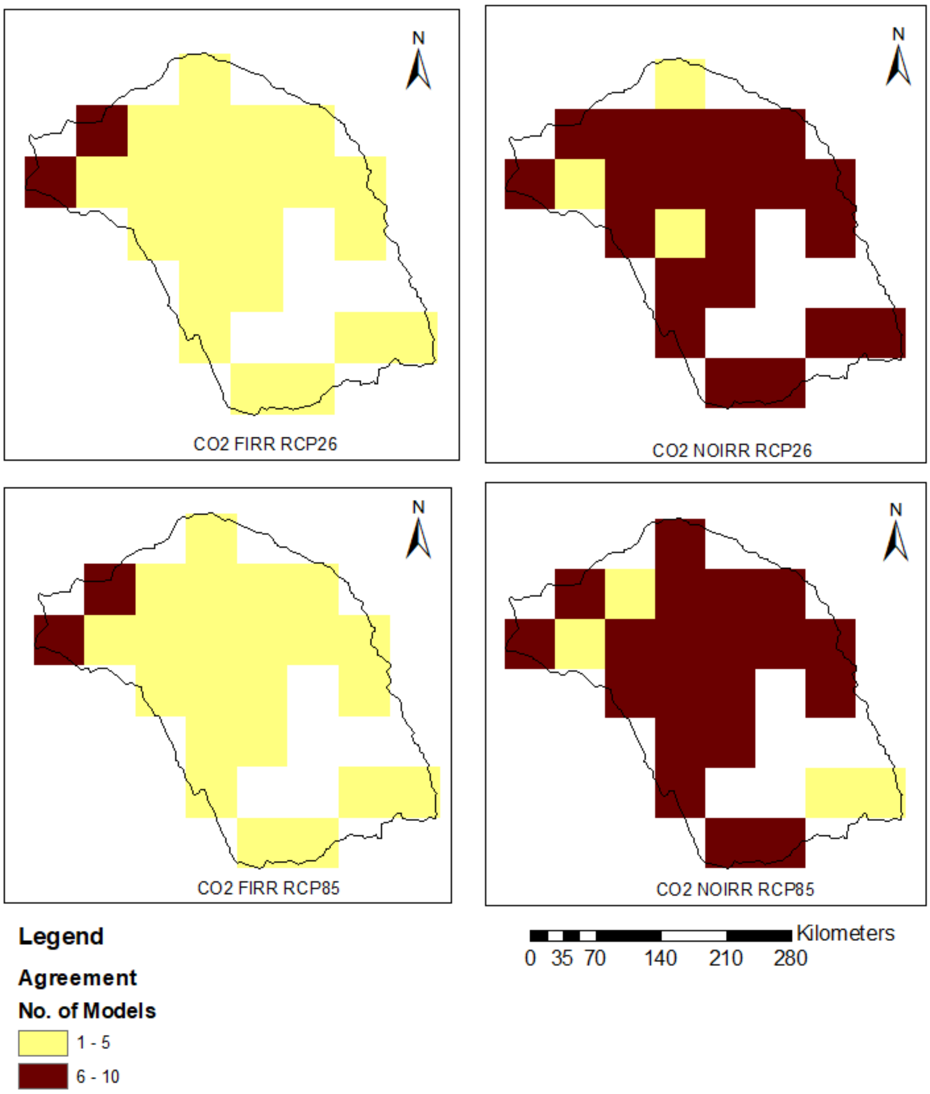

Figure 7-24: Number of simulations resulting in an increase in sorghum yield. The total possible models agreeing is 10.

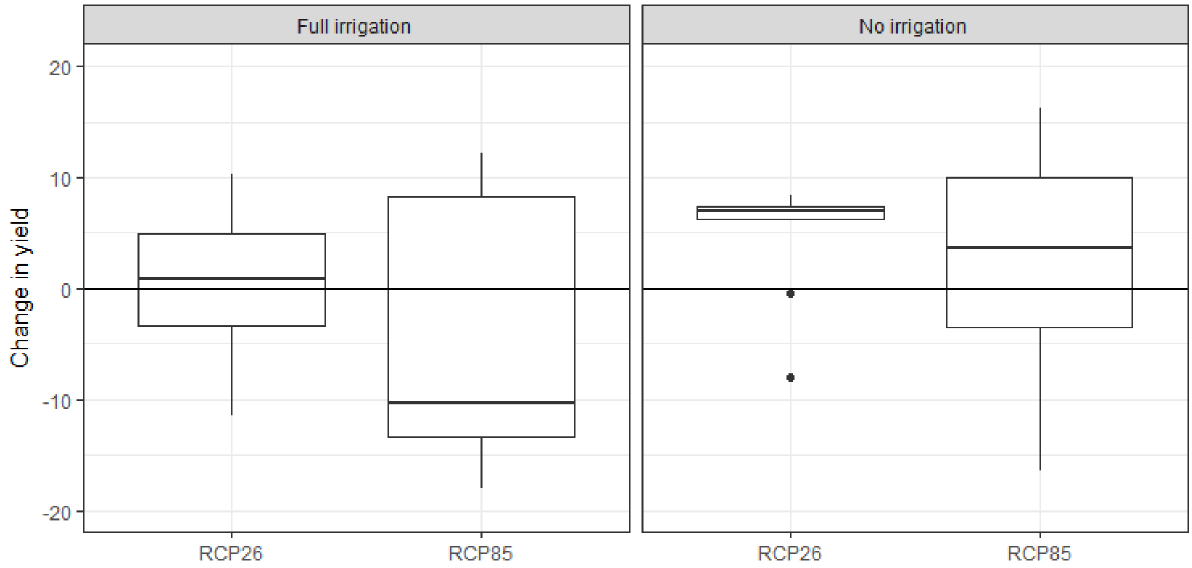

Figure 7-25: Spread of model results for change in total sorghum yield with full irrigation (left) and no irrigation (right) for the two RCPs.

7.4.2.5 Sugarcane

Figure 7-26 shows that the models disagree on the direction of changes in total sugarcane with both full irrigation and no irrigation. IMAGE projects larger changes than the other GGCMs, assuming no irrigation, but also shows sizeable differences between the GCMs within this.

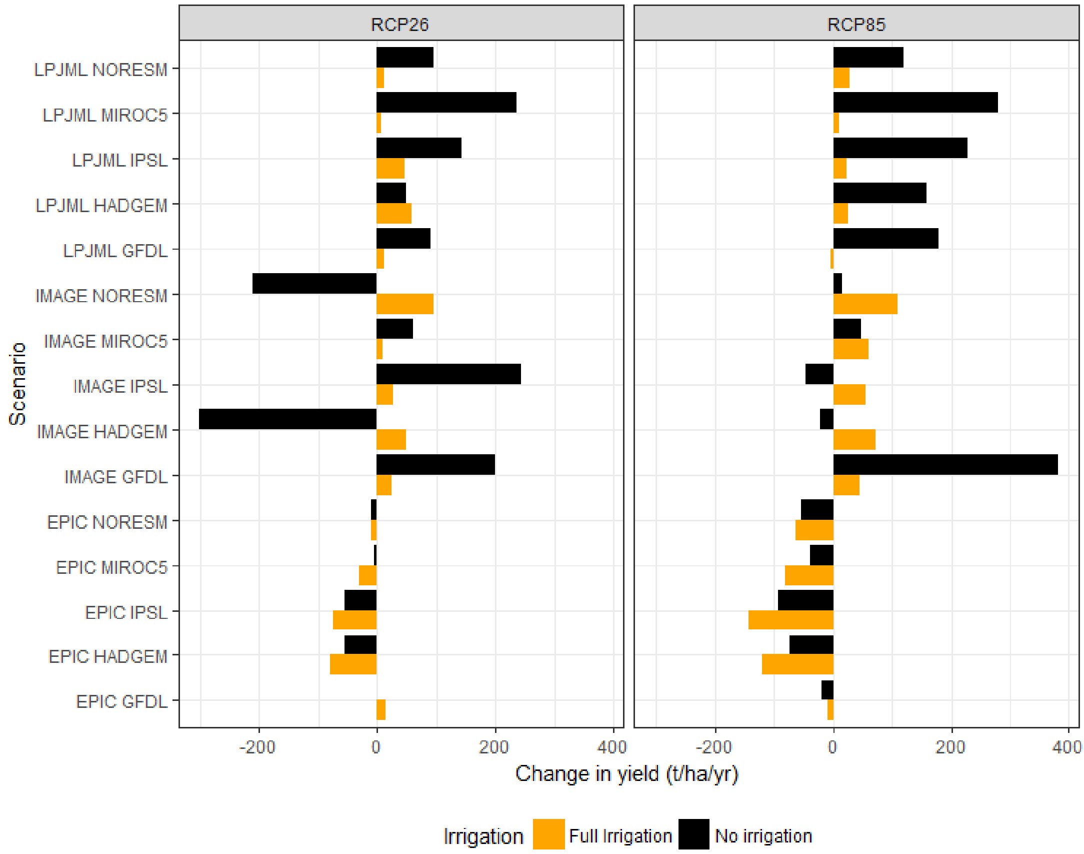

Figure 7-26: Sum of change in sugarcane yield within the Tana River Basin with CO_2 effects for RCP2.6 and RCP8.5

Scenarios without CO_2 fertilisation effects for sugarcane were only available for the LPJML crop model. Changes to total yield for these scenarios are shown in Figure 7-27. Nearly all of the scenarios without CO_2 included lead to increases in sugarcane yield. Generally, the increases in yield are much greater for the no irrigation scenarios than the full irrigation scenarios. The spread of projected changes in sugarcane yield are much higher than seen with the other crops. Figure 7-28 shows the spread of results. When irrigation is included, there is little difference between the scenarios with CO_2 fertilisation included and those without. By contrast, when no irrigation is provided, the scenarios with CO_2 fertilisation effects included generally lead to higher increases in total yield.

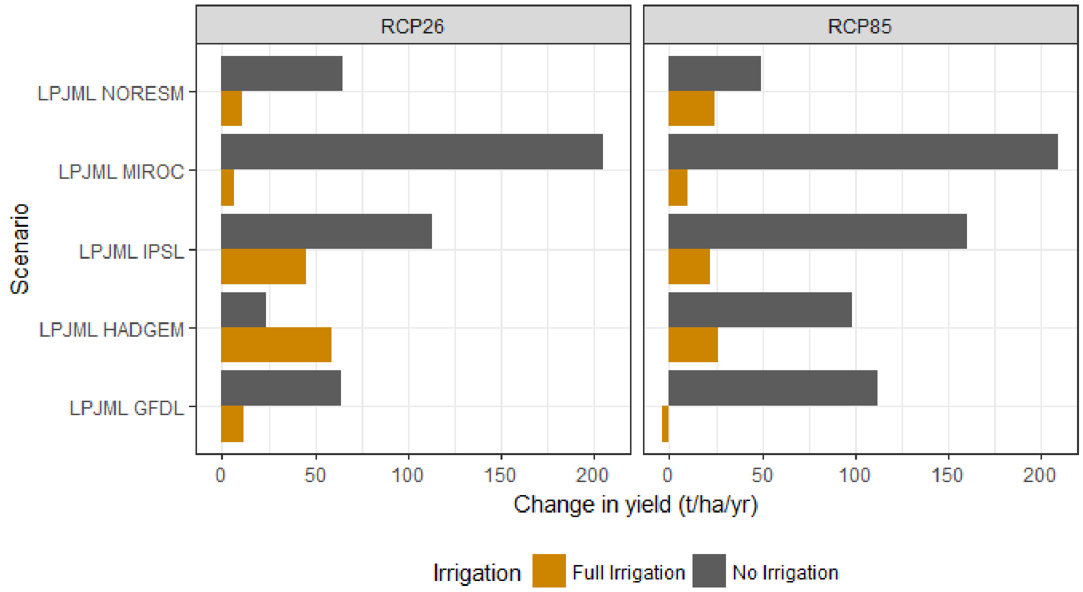

Figure 7-27: Sum change in sugarcane yield within the Tana River Basin without CO_2 effects include for RCP2.6 and RCP8.5

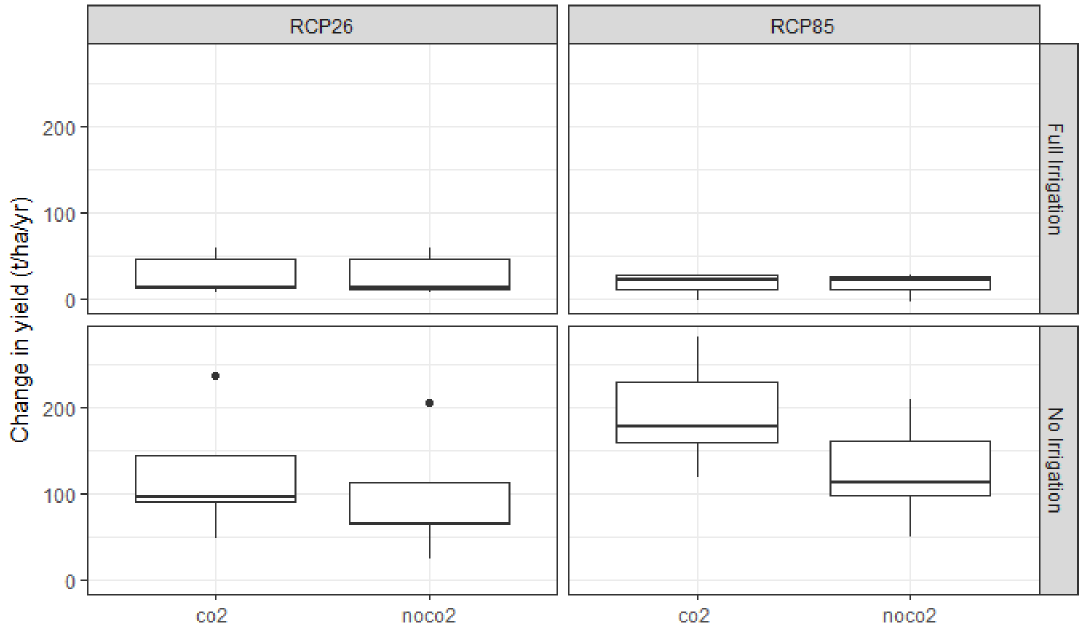

Figure 7-28: Spread of results for changes in total sugarcane yield with and without CO_2, for 2 RCPs and irrigation scenarios.

Figure 7-29 shows that, as with the other crops, there are some individual cells in the north of the basin where the most of models agree that sugarcane yields could increase with CO_2 and full irrigation. Some models project that yields will increase for other parts of the basin.

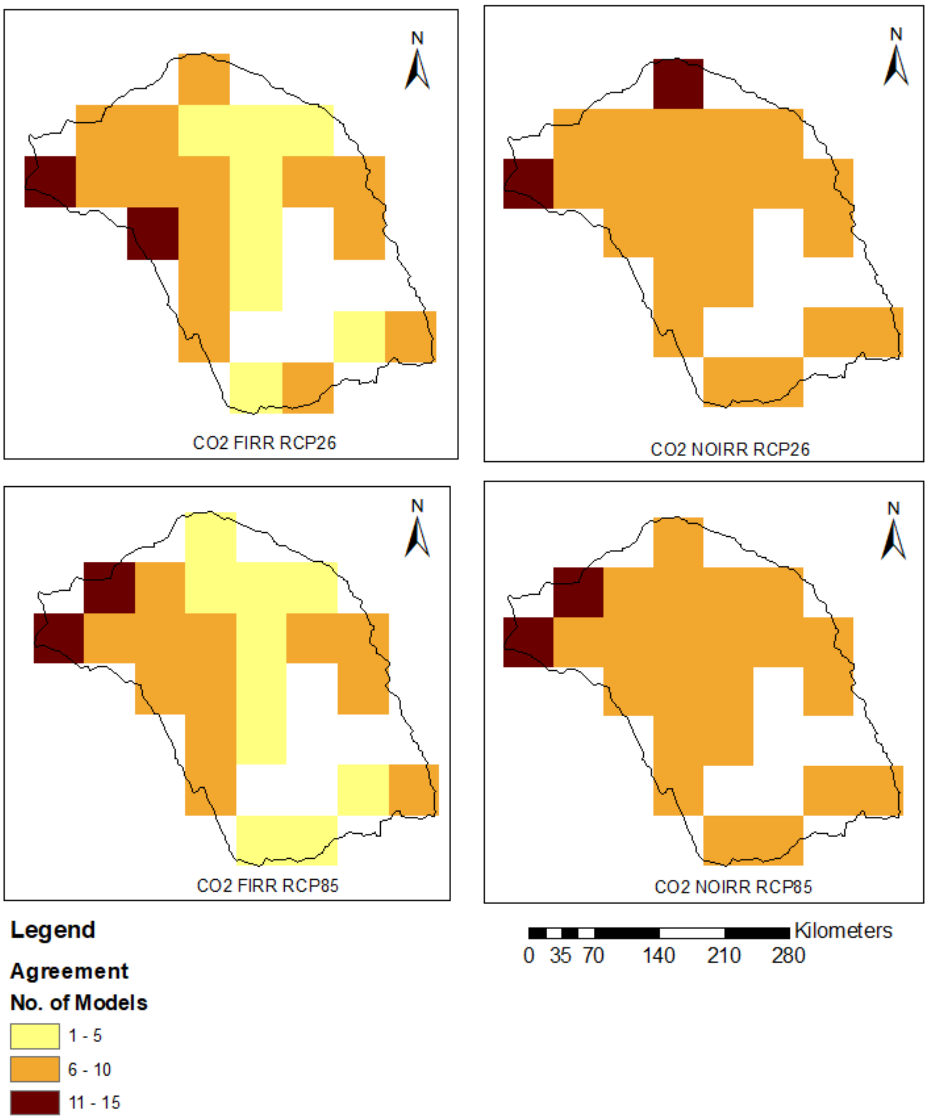

Figure 7-29: Number of simulations resulting in an increase in sugarcane yield. The total possible models agreeing is 15.

7.4.2.6 Comparison between Crops

By comparing the different crops, it is possible to see which is the most positively and negatively affected. As only the EPIC and IMAGE GGCMs are available for all crops, the result from these have been compared first. Figure 7-30 shows the range of projections for maize, millet, sorghum and wheat for these two GGCMs. As the changes to sugarcane yields are much greater in magnitude, they have not been included in this comparison. There is more agreement between the different GGCMs and GCMs for wheat without irrigation scenarios than with full irrigation. A small spread between the individual crop and climate models is also seen for sorghum for RCP2.6, without irrigation included.

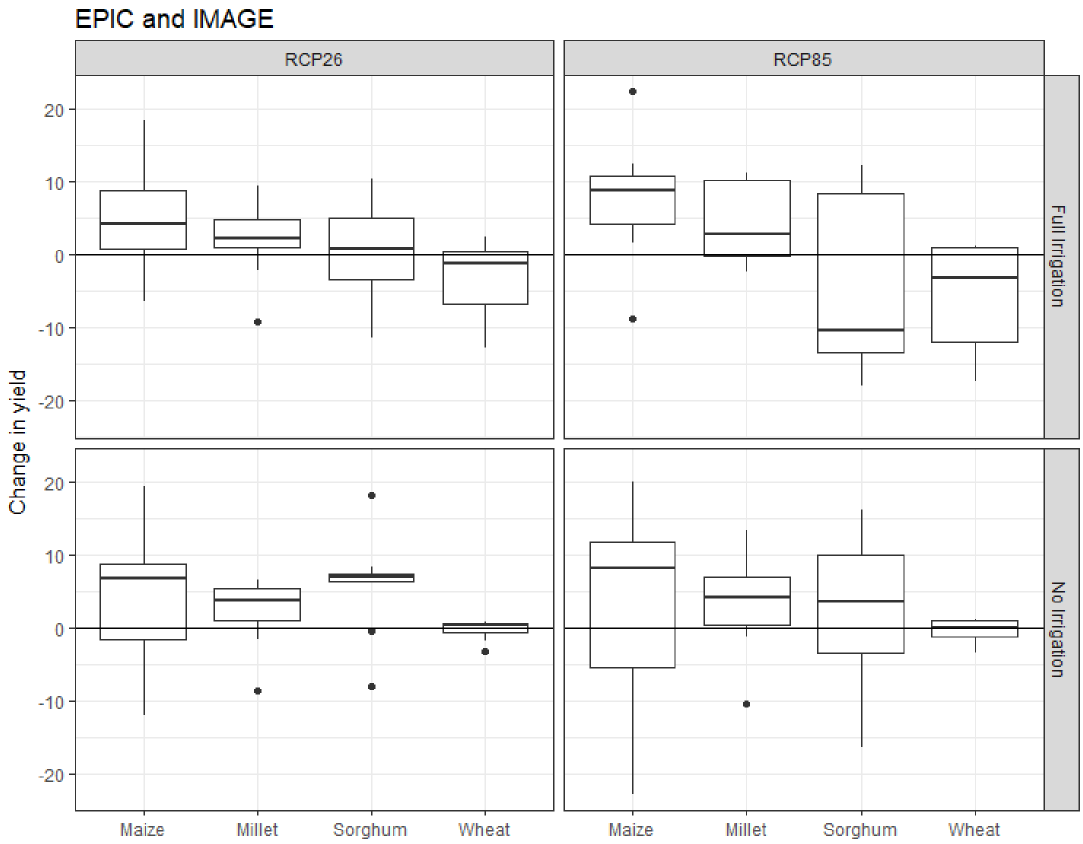

Figure 7-30: Spread of results from the EPIC and IMAGE GGCMs with CO_2 fertilisation effects, for 2 RCPs and irrigation scenarios for maize, millet, sorghum and wheat

Figure 7-31 shows these four crops but with all of the available scenarios with CO_2 effects (all GCMs and GGCMs) included. The majority of models project increases in total yield for millet, regardless of the RCP or irrigation scenario. For the other crops, there is more disagreement on the sign of the change in yield. Figure 7-32 shows the spread of results for the scenarios without CO_2 effects included for maize, millet and wheat. The variation between the individual scenarios is significantly smaller for millet than for maize and wheat. However, fewer individual models were considered for millet. With the exception of maize yields under RCP2.6 conditions without irrigation included, all scenarios where CO_2 effects are not considered lead to reductions in total yield.

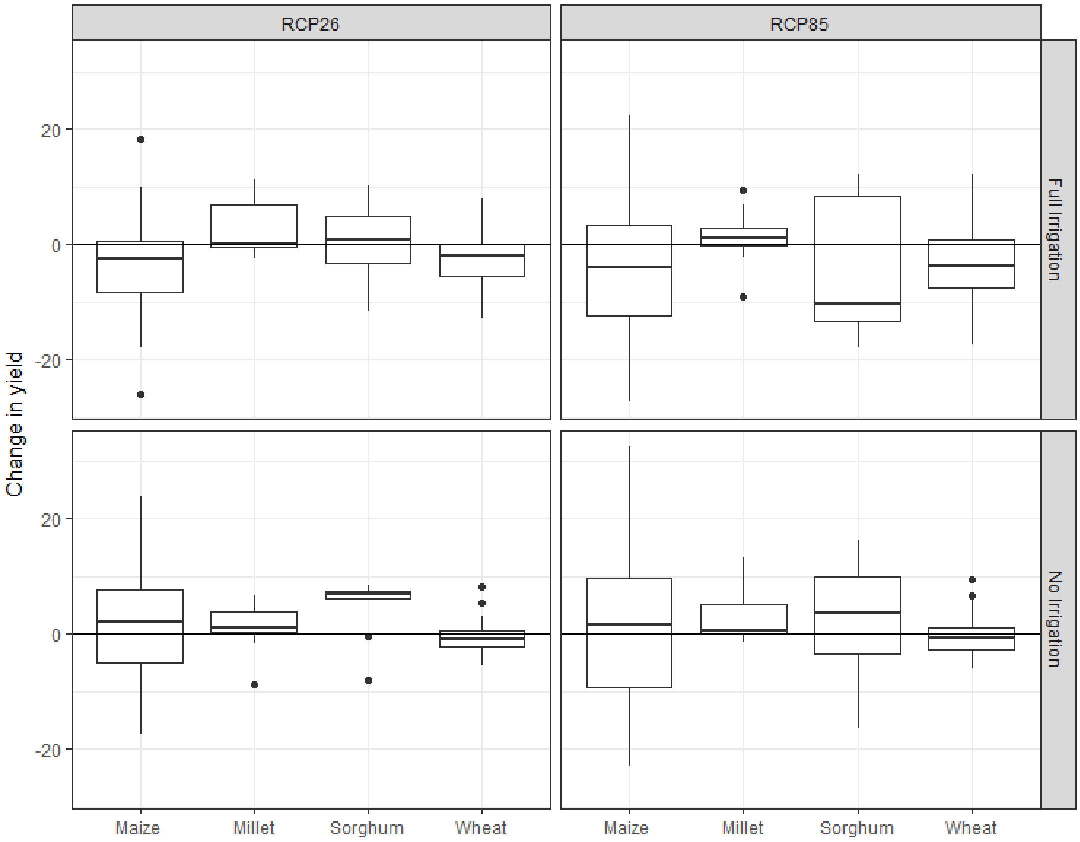

Figure 7-31: Spread of results across all available GCMs and GGCMs with CO_2 fertilisation effects, for 2 RCPs and irrigation scenarios for maize, millet, sorghum and wheat.

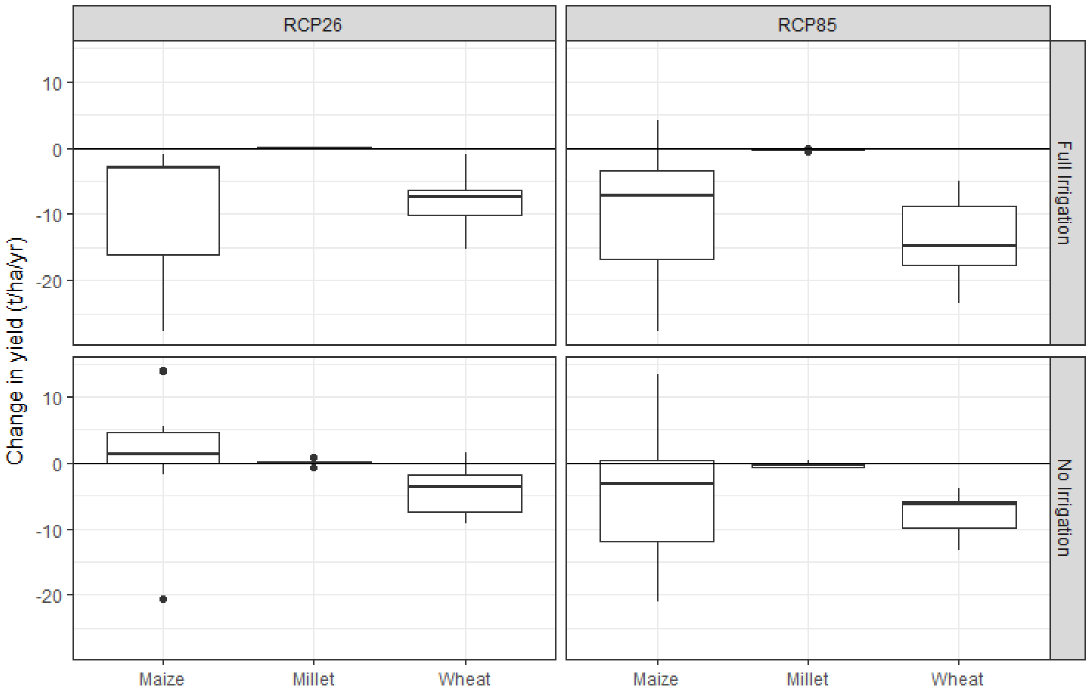

Figure 7-32: Spread of results across all available GCMs and GGCMs without CO_2 fertilisation effects, for 2 RCPs and irrigation scenarios for maize, millet and wheat.

7.4.3 Changes in the Distribution of Used Species

As well as the major crops above, some used species are likely to experience increases in the area suitable, whereas others are likely to see reductions in the land suitable for growth. In the following figures, the used species have been split into categories based on their use or importance. Figures 7-33 and 7-34 show the crop species (cash crops, fruits and legumes). Figure 7-39 shows the agroforestry species and Figure 7-40 shows the afforestation species.

7.4.3.1 Crop Species

Figure 7-33 shows that there are substantial reductions in the land suitable for the three legumes. The pigeonpea is the most sensitive to higher temperatures. Reductions in the number of cells suitable for growth are also seen for the three cash crops. The changes to the fruit crops are more varied. Papaya, avocado and tomato see large reductions in the area suitable with higher levels of warming, while mango and pineapple do not.

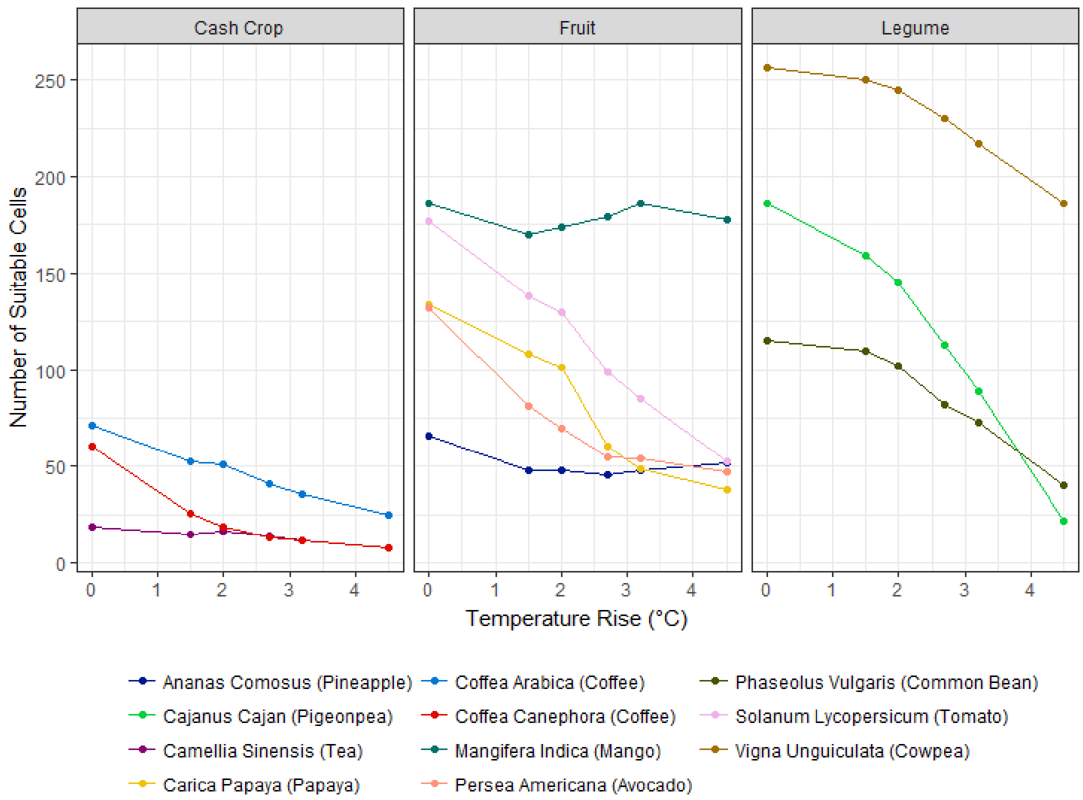

Figure 7-33: Number of cells (count) suitable for crop species in the Tana River Basin with different levels of warming. Crop species are split into cash crops, fruit and legumes. Data are presented as the mean across 21 alternative climate models.

However, by examining the mean suitability instead (Figure 7-34), some crop species show increases in average suitability across the basin. Avocado, pineapple, mango and tomato see some minor increases in suitability with warmer temperatures. Of the cash crops, *Coffea arabica* shows a reduction in the number of suitable cells, but an increase in the average suitability. This suggests that the distribution will become more limited but that it is the marginal areas that will be lost. Pigeon pea, cowpea, the common bean, tea and papaya are projected to see decreases in both average suitability and the number of cells suitable.

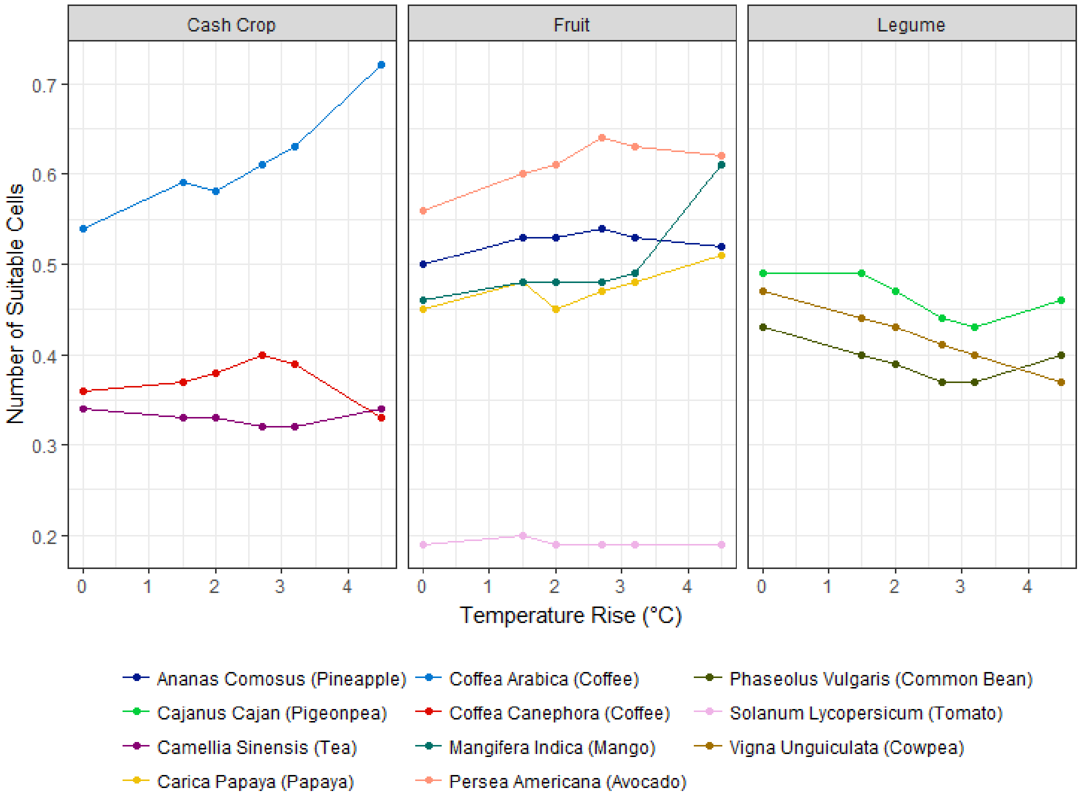

Figure 7-34: Mean suitability for crop species within the Tana River Basin with different levels of warming. Crop species are split into cash crops, fruit and legumes. Data are presented as the mean across 21 alternative climate models.

Table 7-9 describes the main changes in the distribution of the used species spatially. The crops with the highest agricultural value in the table are tea and coffee. The area of the Tana River Basin suitable for tea growing under current conditions is limited to the upland areas in the north of the basin. Similarly, arabica coffee growing regions are limited to the slopes in the north and west of the basin under current climatic conditions. The area suitable for both tea and coffee production is likely to decrease with greater levels of warming. The less common variety of coffee (*coffea canephora*, commonly referred to as robusta) also experiences reductions in the land suitable, but the distribution of suitable land is different from the arabica coffee variety. Robusta coffee can be grown at lower elevations and so land suitable is found on the slopes in the west of the basin, rather than just the mountains in the north.

Other important crops include cowpea, pigeonpea and beans. There are reductions in the areas that are highly suitable for both cowpeas and pigeonpeas projected. The common bean also experiences decreases in the land that is suitable. There are no areas that are highly suitable in the future under any degree of warming. There is a contraction in the land suitable for bean growth in the north of the basin.

Increases in the area suitable for both mango and pineapple growth are projected with rises in temperature. The floodplains and rangelands in the central area of the basin are projected to become more suitable as the climate warms.

Other fruits, such as avocado and tomato, are likely to see reductions in the land suitable for growth. The changes in the land suitable for tomato growth are marked. Areas of the basin that are moderately suitable decrease substantially with greater levels of warming. With only 1.5°C of warming, the band of currently suitable land closest to the basin outlet at the coast is lost completely. The suitable area in the west of the basin reduces in size significantly with higher levels of temperature increase. There are very few cells with a high suitability under current conditions, however, changes to these areas are also seen with future temperature rise. Similarly, the area that is suitable for avocado growth is limited to the highlands in the north of the basin as the temperature rises. Although not grown for export, papaya is also an important fruit in Kenya. The majority of the Tana River Basin is suitable for papaya growth under current climate conditions. As temperatures increase, the band of suitable land in the southern half of the basin becomes unsuitable. By 4.5°C of warming, the area suitable becomes limited to the north and west of the basin.

Table 7-9: Main changes in the used species, the arrows show the general direction of change in suitability.

Species	**Direction of change**	**Description of major changes**
Tomato	↓	Suitable area in the west of the basin reduces in size significantly with higher levels of temperature increase.
Cowpea	↓	Band of moderately suitable land closest to the delta region decreases with higher levels of warming.
Pigeon pea	↓	Large contractions in the area suitable
Avocado	↓	With large temperature increases, the area suitable is limited to the highlands in the north
Mango	↑	Increases in the area highly suitable in the central part of the basin.
Pineapple	↑	Areas that are highly suitable increase with higher levels of warming. Temperature increases of 4.5°C lead to central Tana River Basin becoming highly suitable for pineapple growth.
Papaya	↓	Large reductions in the area suitable.
Common bean	↓	Decreases in the land that is moderately suitable
Coffee (arabica)	↓	Contractions in the area suitable, suggesting that moving to higher altitudes.
Coffee (robusta)	↓	Contraction in the land suitable, distribution becomes more patchy
Tea	↓	Contractions in the land suitable

The multi-model mean climate change scenarios from WaterWorld, presented in Chapter 4, Section 5.1, project an increase in basin-average mean annual temperature of around 2°C by the 2050s. Therefore, the 2°C scenario from the Wallace 3 database has been presented here to examine the spatial patterns of suitability for different used species. The areas of suitable land overlap for the different species, but this is useful for seeing the areas where the land is only suitable for one species. The species with the greatest area suitable with 2°C of warming is the bottom layer and the species with the smallest distribution is at the top. For the following figures, the crop species have been split into the same categories used for the graph above (i.e. high-value cash crops, fruits and legumes).

Figure 7-35 shows the areas suitable for tea and coffee growth with 2°C of warming. The land suitable for tea production is extremely limited. A greater area is suitable for both species of coffee. All three species are confined to the upslope areas with 2°C of warming.

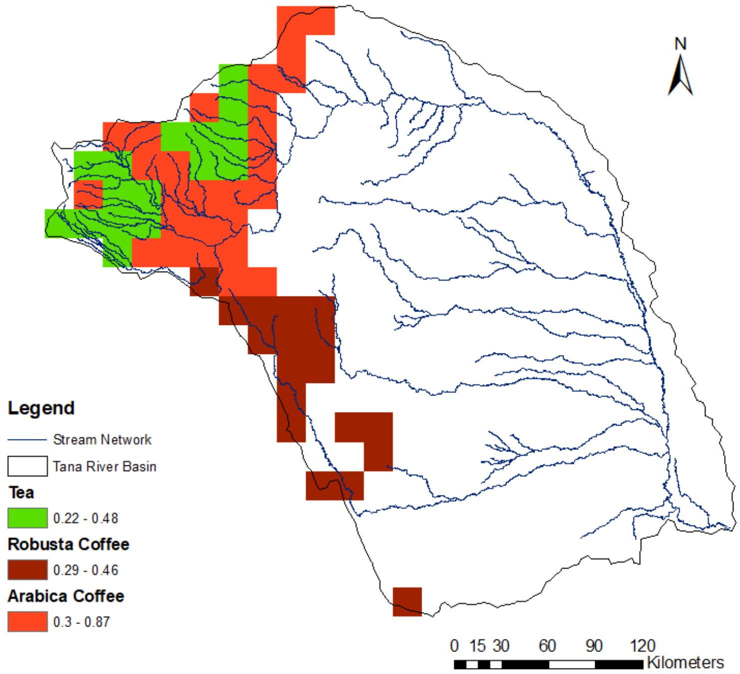

Figure 7-35: Area suitable for tea (green), arabica coffee (pink) and robusta coffee (brown) with 2°C of warming. The numbers in the Legend show the range in suitability for each species. Data are presented as the mean across 21 alternative climate models.

A similar map for the fruit species is presented in Figure 7-36. The areas suitable for pineapple growth are in the very north and very south of the Tana River Basin. Avocados can be grown on the hills in the west of the basin. Despite seeing a reduction in the average suitability, there is still a sizeable area of the Tana Basin suitable for tomatoes with 2°C of warming. Papaya becomes more restricted, to an area in the south and central Tana River Basin. Mango is the species with the largest area suitable on this figure, but it is largely hidden beneath the other layers. There are cells that are only suitable for mango in the eastern half of the basin.

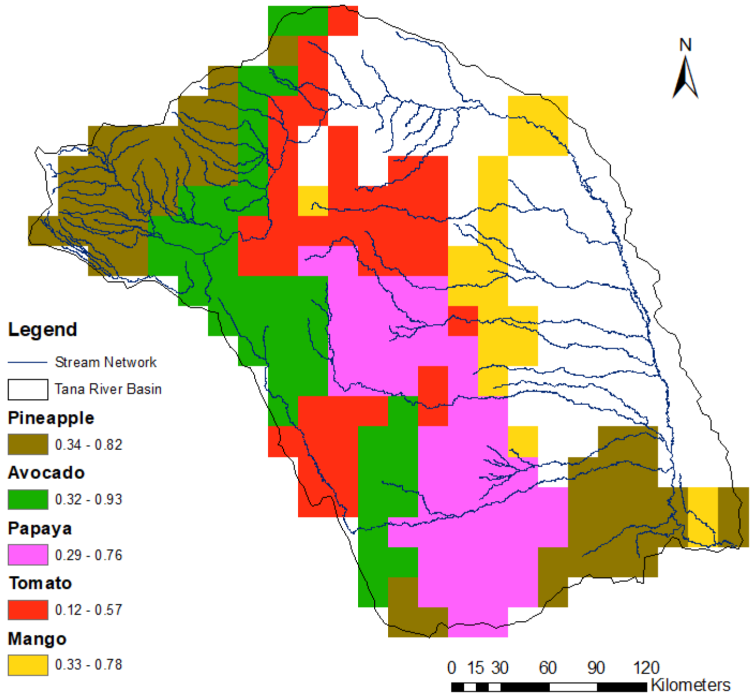

Figure 7-36: Areas suitable for the different fruit species with 2°C of warming. The numbers in the Legend show the range in suitability within the suitable cells for each species. Data are presented as the mean across 21 alternative climate models.

Figure 7-37 shows the three remaining crop species: cowpea, pigeonpea and common beans. The majority of the basin remains suitable for cowpea growth, but smaller areas of the basin are suitable for pigeonpea and beans.

By combining these maps, it is clear that the upper Tana basin remains, or becomes, suitable for many used species, including tea, coffee, pineapple and beans. This is likely to lead to trade-offs between species, with those with the highest economic value being favoured.

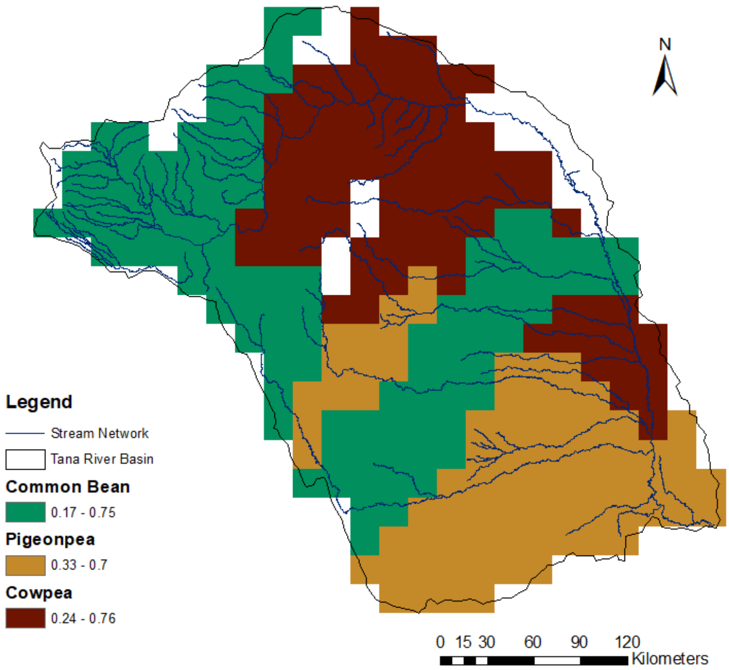

Figure 7-37: Areas suitable for common beans (green), pigeonpea (beige) and cowpea (brown) with 2°C of warming. The numbers in the Legend show the range in suitability within the suitable cells for each species. Data are presented as the mean across 21 alternative climate models

7.4.3.2 Agroforestry and Afforestation Species

Significant changes are also projected for the agroforestry species as shown in Figure 7-38. *Acacia tortilis*, *Sesbania sesban* and *Leucaena leucocephala* are sensitive to higher temperatures. Some species, such as *Markhamia lutea* and *Grevillea robusta*, have a low number of suitable cells under current conditions. The area suitable does not change much with warmer conditions. By contrast, *Tamarindus indica* maintains a high number of suitable cells in the basin with all levels of warming.

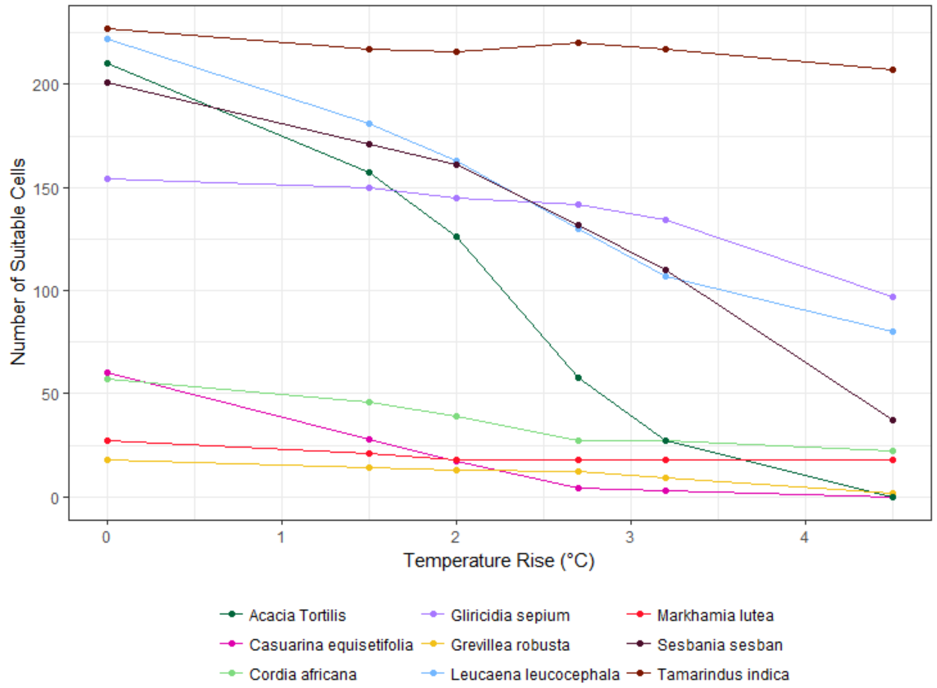

Figure 7-38: Number of suitable cells within the Tana River Basin for agroforestry species with higher temperatures. Data are presented as the mean across 21 alternative climate models.

Figure 7-39 shows the changes in the area suitable for the species recommended for afforestation. The relatively low number of cells suitable for the Ecozone II and Ecozone III – Highlands species under current conditions can be explained by the small area of the basin within these zones. However, the majority of these species see a reduction in the number of suitable cells with higher temperatures. Similarly, reductions in the suitable climate space are seen for nearly all of the other afforestation species. One exception is the neem tree (*Azadirachta indica*). The majority of the basin is suitable for this species under current climate conditions and there is no change in the suitable climate space with warming.

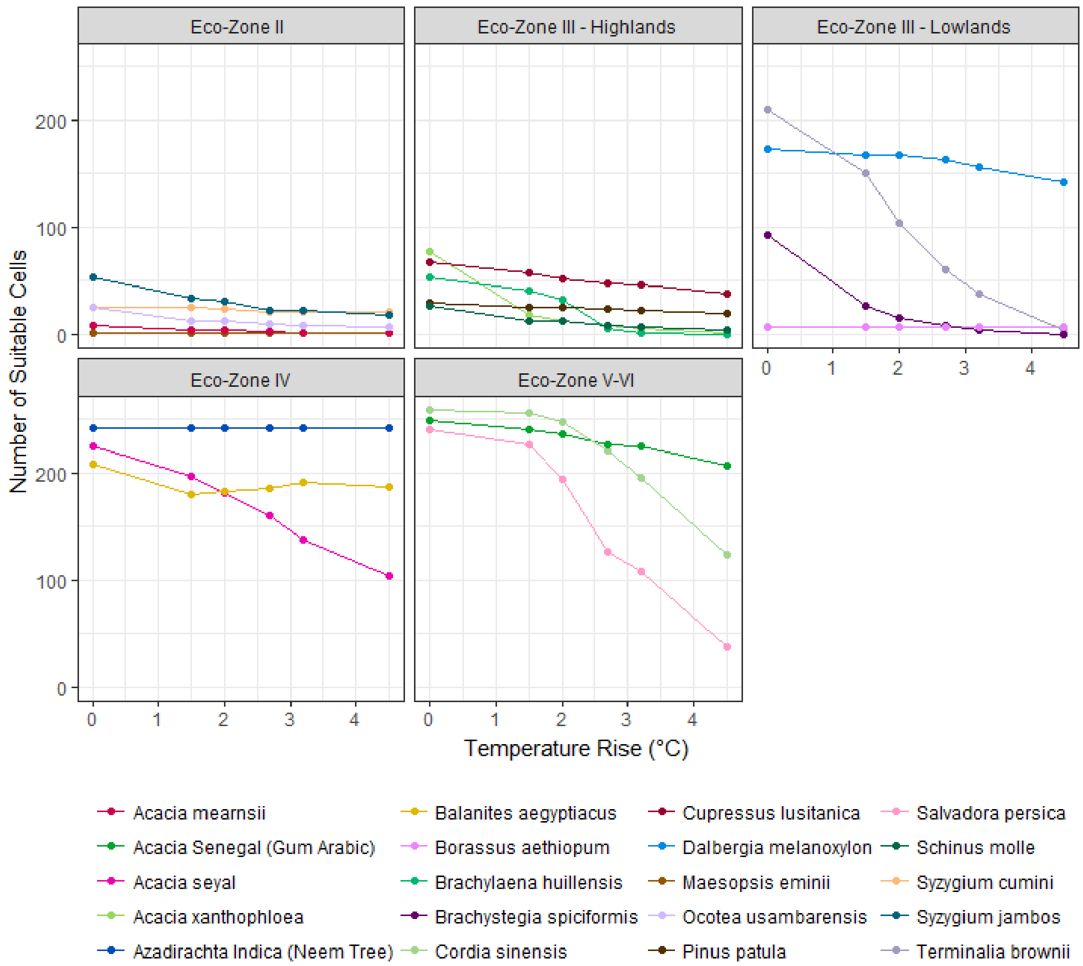

Figure 7-39: Number of suitable cells for tree-planting species within the Tana River Basin with higher temperatures, split into the eco-zone that the tree species are recommended for. Data are presented as the mean across 21 alternative climate models.

7.4.4 Soil Properties

Soil nutrient availability is derived from specific soil qualities: soil texture, soil organic carbon, soil pH and total exchangeable bases, which are read from the Harmonised World Soil Database (IIASA/FAO, 2012). Figure 7-40 shows the variation in nutrient availability across the Tana River Basin. Soil nutrient availability varies across the basin, but moderate or severe constraints are found in large areas. There are also extents with no or slight constraints.

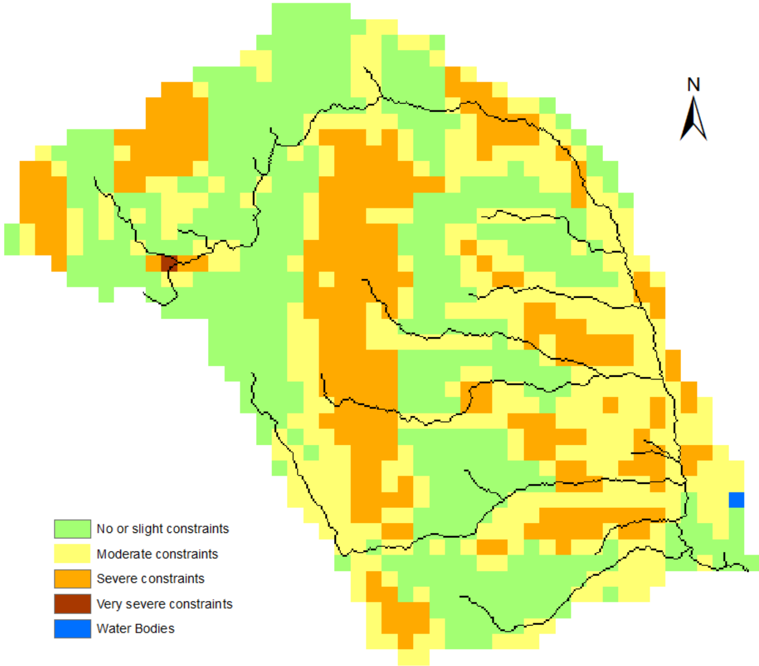

Figure 7-40: Soil nutrient availability across the Tana River Basin. Source: FAO/IIASA, 2011-2012. Global Agro-ecological Zones (GAEZ v3.0; IIASA/FAO, 2012).

By contrast, the majority of the basin see no constraints to soil workability, as shown in Figure 7-41. Soil workability, or ease of tillage, is estimated from soil texture, effective soil depth/volume and soil phases constraining soil management (IIASA/FAO, 2012). There are some areas close to the river in the upland region and east of the basin that show severe constraints to soil workability.

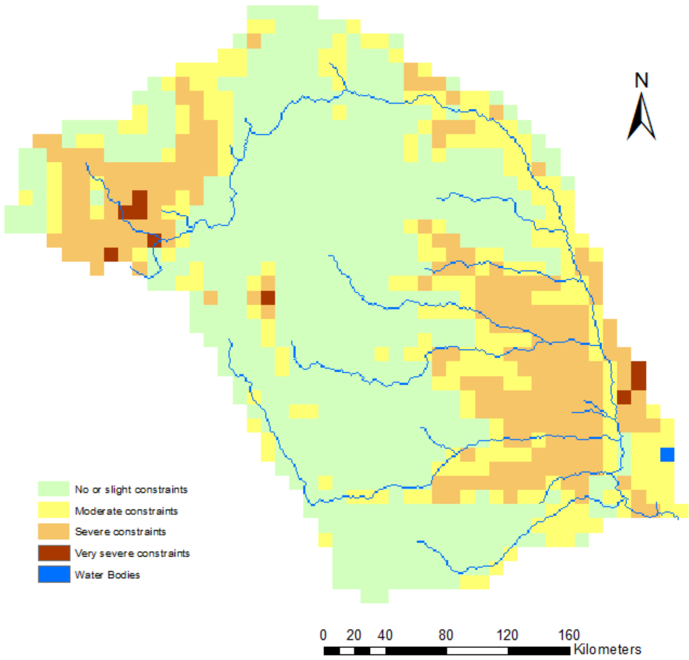

Figure 7-41: Soil workability within the Tana River Basin. Source: FAO/IIASA, 2011-2012. Global Agro-ecological Zones (GAEZ v3.0; IIASA/FAO, 2012).

7.4.5 LUH2 Cropland and Pasture Changes

LUH2 data was used to determine the proportion of each cell containing cropland or pasture, historically and in the future. Cropland is the combined proportion of C3 annual, C4 annual, C3 perennial, C4 perennial and C3 nitrogen fixing crops. The basin-mean proportion generally increases with the higher RCPs (Figure 7-42). Similarly, the proportion of pasture within the basin generally increases with higher RCPs, as shown in Figure 7-43. The proportions of cropland increase most in the northwest of the basin but higher proportions can be seen across the basin (compared to the historical values) seen with all RCPs for the 2050s.

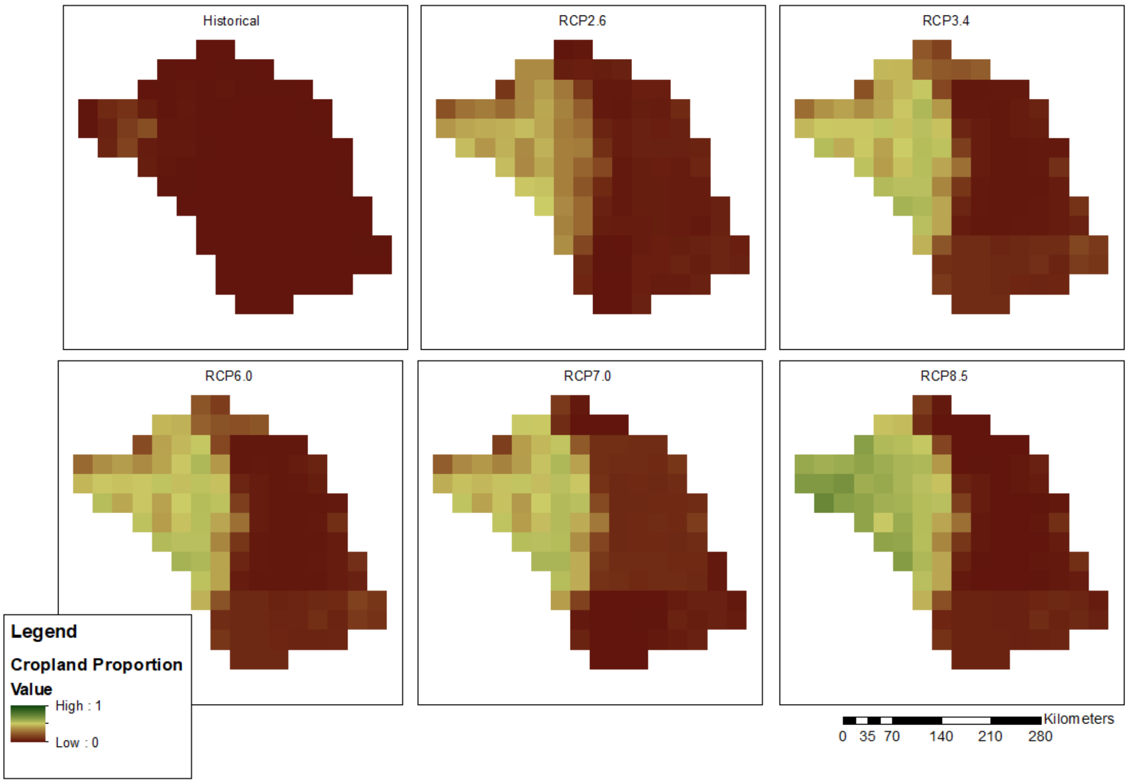

Figure 7-42: Historical cropland proportion within the Tana River Basin and projected changes with the different RCPs

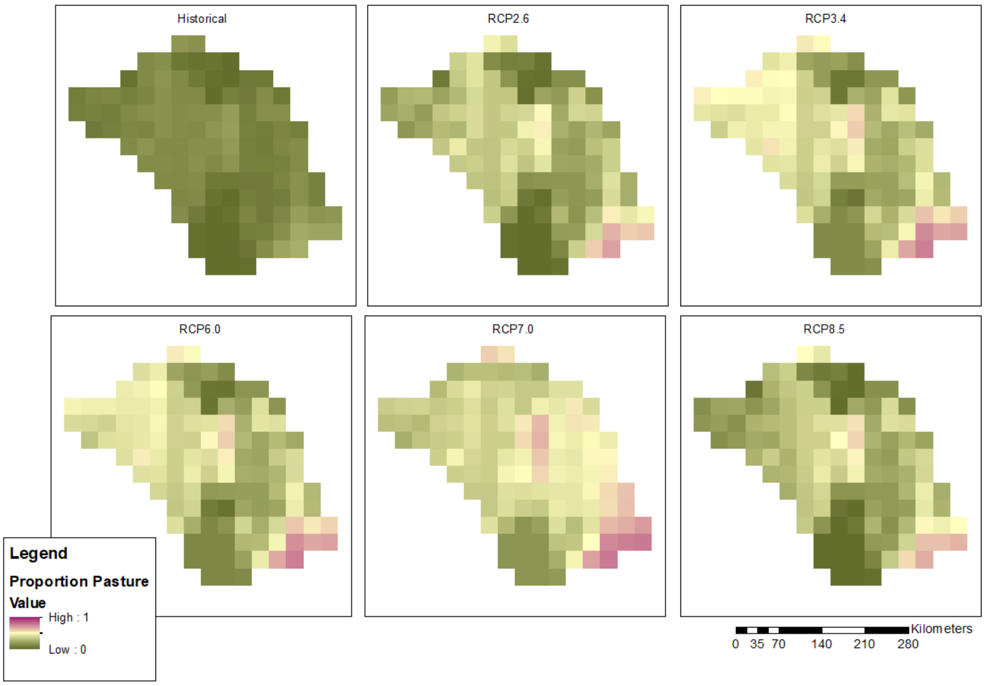

Figure 7-43: Historical pasture proportion within the Tana River Basin and projected changes with the different RCPs

Figure 7-44 shows the difference between the historical proportions of cropland and pasture and the future, using RCP8.5. The greatest increases in cropland occur in the northwest of the basin. This has been shown to be the area where agricultural is already largely focused. The greatest increases in pasture occur along the coastal region and along the main river. There is also an area of increase in the central rangelands.

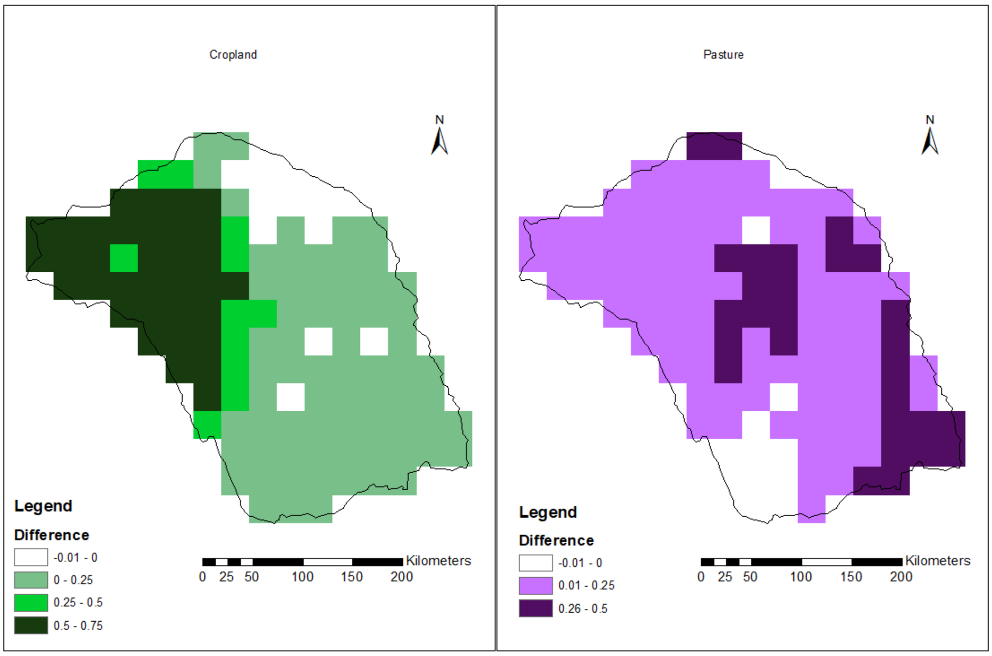

Figure 7-44: Projected changes to the proportion of cropland (left) and pasture (right) within the Tana River Basin between historical scenario and RCP8.5

7.4.6 Comparison with Management Plans

Relevant features of GoK management plans were digitised from maps included in the reports into polygons and polylines using ArcMap software to ensure the correct coordinates were collected. This was necessary as original GoK data was not provided with the reports and could not be easily obtained. This geographically referenced information was then compared to the results from previous chapters, to evaluate the relationships between the different sectors. Many features were taken from the National Spatial Plan (GoK, 2017). Information on important wildlife corridors were digitised from maps included in the Report on Wildlife Corridors and Dispersal Areas (Ojwang' *et al.*, 2017). The main features from the National Spatial Plan within the Tana River Basin are shown on Figure 7-45.

The National Spatial Plan focuses developments in specific areas within the basin. The area in the north of the basin contains most of the high and medium potential agricultural land, as well as large proposed irrigation area and a proposed growth area. Proposed hydropower stations along the main river are still included in the National Spatial Plan. These are further downstream than the existing hydropower stations. The proposed irrigation area in the upper basin appears to coincide with these hydropower stations and dams.

The LAPSSET corridor runs along the eastern edge of the Tana River Basin, with parts of the railway line and main road passing through the basin. The railway line continues through the high-potential agricultural land in the north of the basin on to Nairobi. Two new airports are proposed just outside the boundaries of the Tana River Basin; one in the north and one in the south near the coast. These are likely to impact on areas of the basin. Another area of proposed irrigation land runs next to the river in the lower part of the basin.

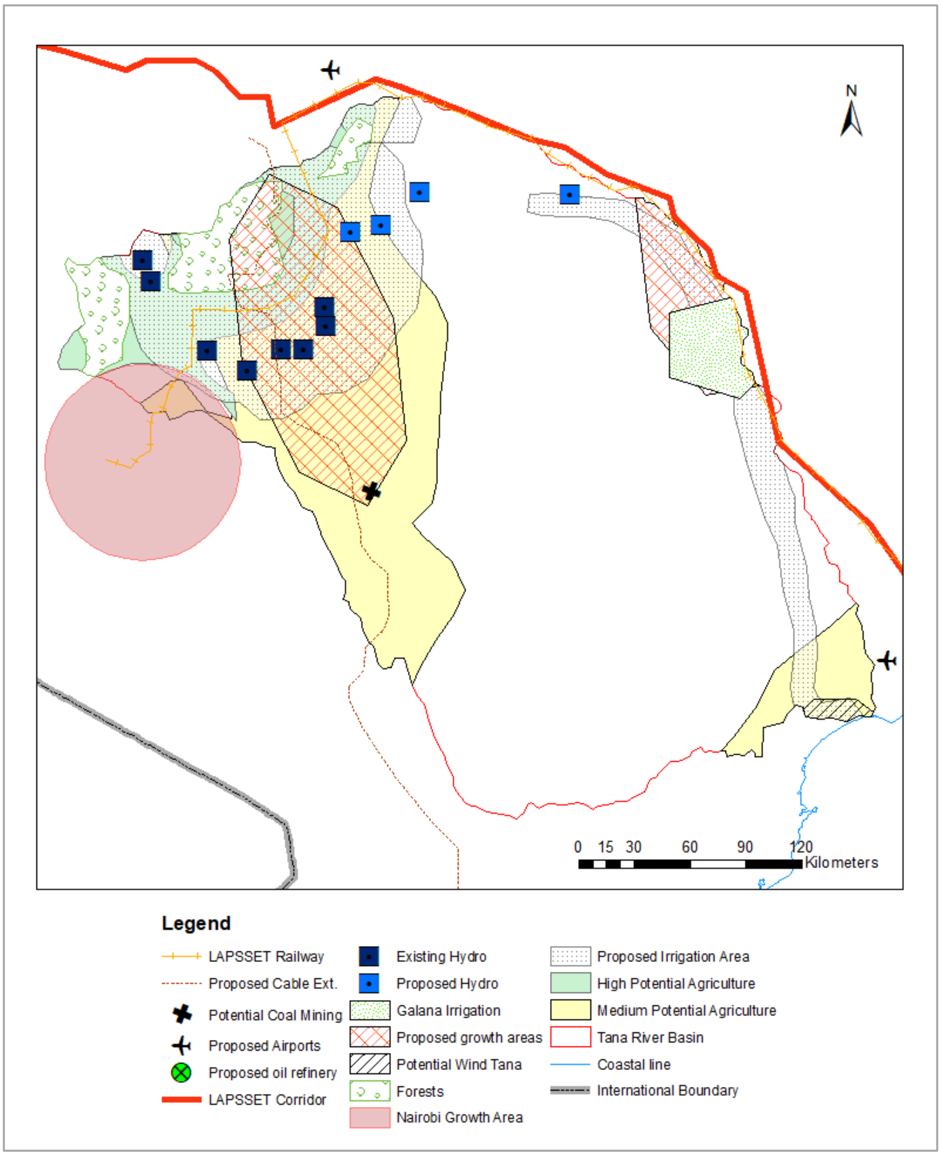

Figure 7-45: Key elements of the National Spatial Plan (GoK, 2017) within the Tana River Basin, digitised using ArcMap software.

Figure 7-46 shows important wildlife corridors and areas of human-wildlife conflict which were identified in the Wildlife Corridors and Dispersal Areas Report (Ojwang' *et al.*, 2017). These corridors were identified and prioritised using an adapted version of the Driver-Pressure-State-Impact-Response (DPSIR) framework. Data on the movement and population trends in six key species (elephant, Grevy's zebra, Burchell's zebra, oryx, giraffe and topi) were used to define the corridors. Climate change was not considered in the development of the corridors, but the authors acknowledge that it will become a key challenge for wildlife in the future and that including climate change is an essential next step. Important wildlife corridors are seen between the Rahole National Reserve, Kora National Park and Bisanadi National Reserve in the north of the basin, as well as between South Kitui National Reserve and Tsavo East National Park in the south.

The Galana Ranch, in the south of the Tana River Basin, provides an important corridor for wildlife passing into and out of the Tsavo East National Park alongside. This ranch is now run as a wildlife conservancy. An extensive area of existing human-wildlife conflicts in the basin occurs at the Tana River Delta and along the coast.

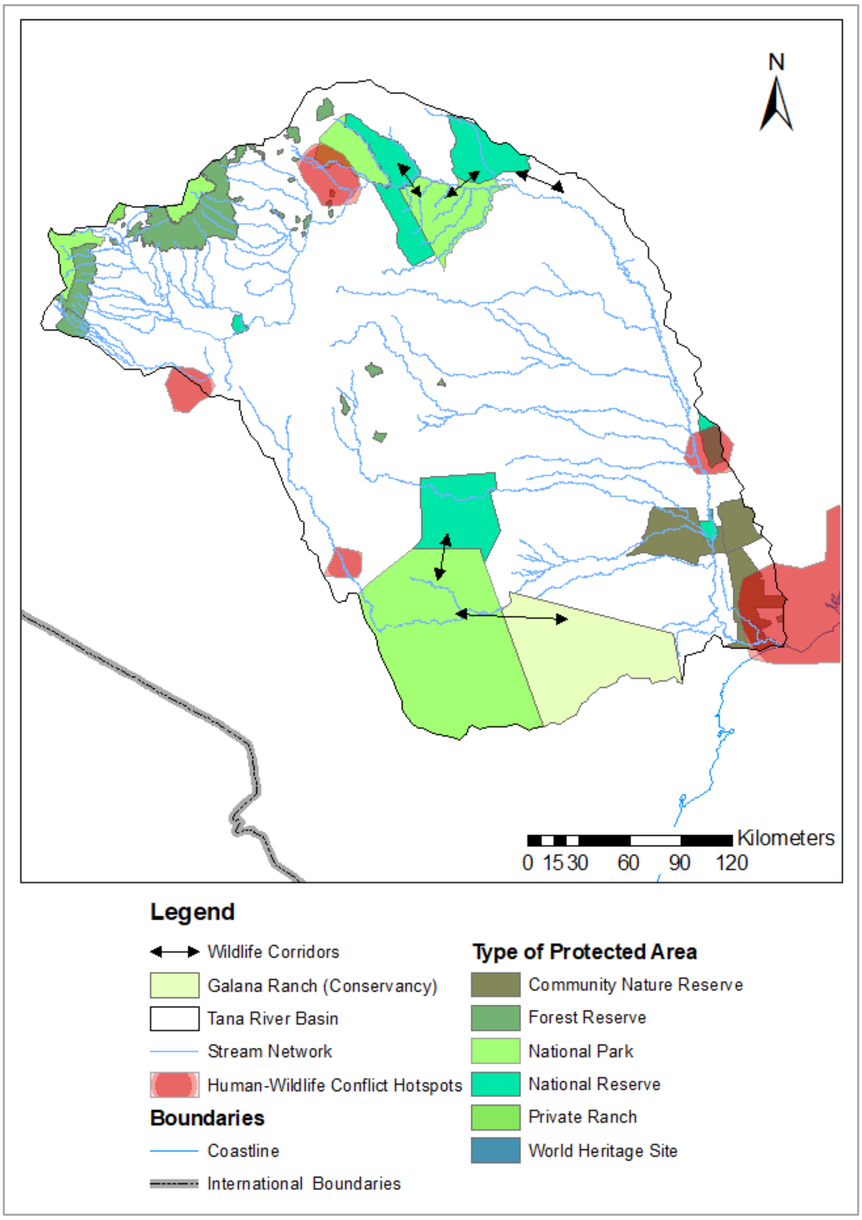

Figure 7-46: Important features of the Wildlife Corridors and Dispersal Areas Report (Ojwang' et al., 2017) within the Tana River Basin, digitised using ArcMap software.

7.5 Integrating results within and across sectors

This section will combine results for the different sectors (water, biodiversity and agriculture) from this and the previous 3 chapters to show cross-sectoral interactions and aggregate potential risks and trade-off hotspots.

7.5.1 Current Agriculture and Climate Refugia

Fewer studies have focused on the impacts of land use change on biodiversity than on climate change (Titeux *et al.*, 2016), so this is an important topic of research. Refugia for plants in the north of the basin have been compared to the current agriculture. From Figure 7-47, it is clear that some potential refugia for plants have already been converted for agriculture. Projected refugia are concentrated in the north of the basin and along the main river into the delta region. There is a range of agriculture already in these areas. With half of these areas already converted to agriculture, it is possible that many native plants will be lost if the temperatures rise and radiative forcing reaches this level. For RCP8.5, there are no areas where 15 or more GCMs identify refugia, as shown in Chapter 6, so a map of this has not been included in this section.

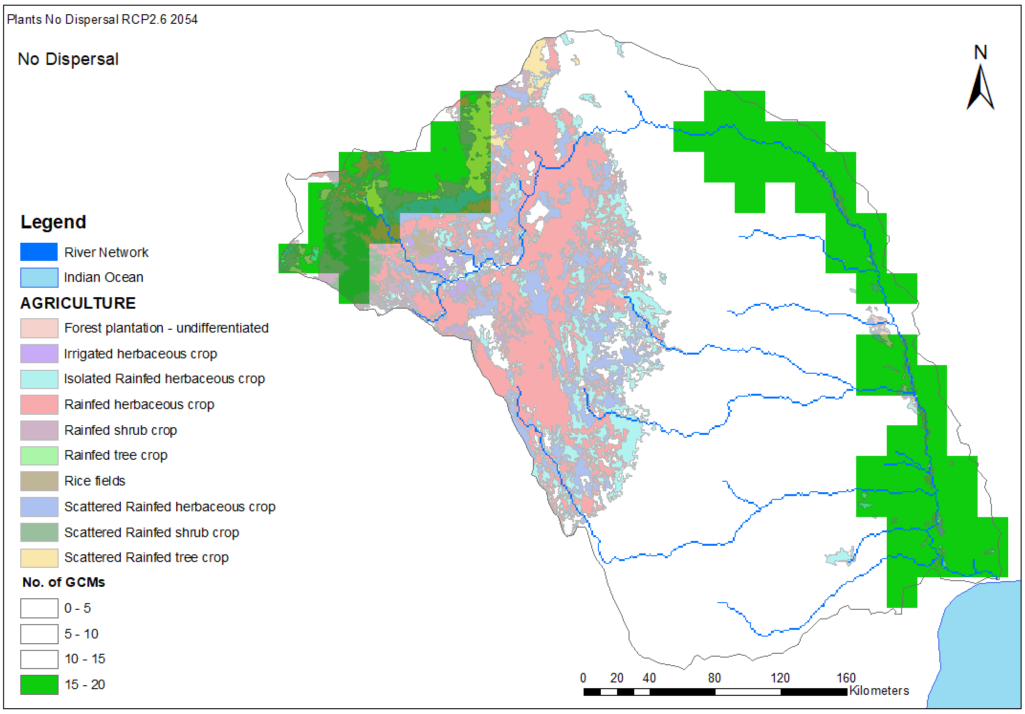

Figure 7-47: Number of GCMs agreeing on the location of refugia for plants for RCP2.6 by 2054 compared to current agriculture within the Tana River Basin (Agricultural Data from World Resources Institute, 2007)

The same can be seen for mammals. For mammals, two dispersal scenarios were considered. Assuming no dispersal, the refugia are extremely limited, as shown in Figure 7-48. This map shows the agreement between the models for RCP8.5. The refugia are concentrated in three main areas; the mountains near the source of the Tana River, the mid reaches in the northeast of the basin and in the Tana Delta area at the coast. However, if mammals are allowed to disperse at a realistic rate, many more cells of the basin become potential refugia (shown in Figure 7-49).

This means that there is not as much conflict between refugia and current agriculture and shows the importance of maintaining landscape connectivity.

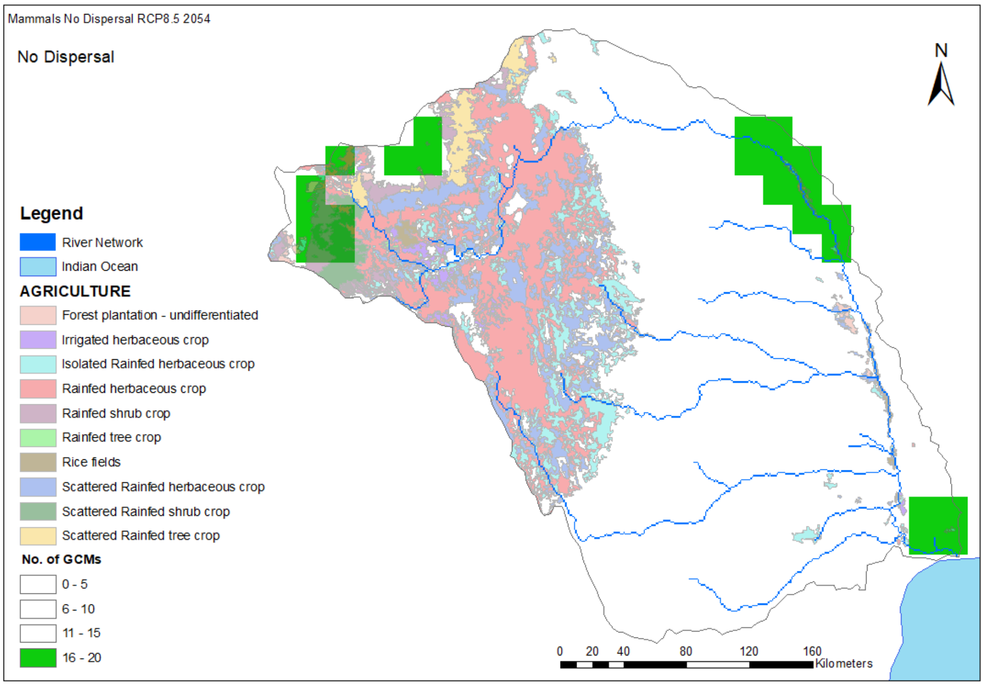

Figure 7-48: Number of GCMs agreeing on the location of refugia for mammals for RCP8.5 by 2054, assuming no dispersal, compared to current agriculture within the Tana River Basin

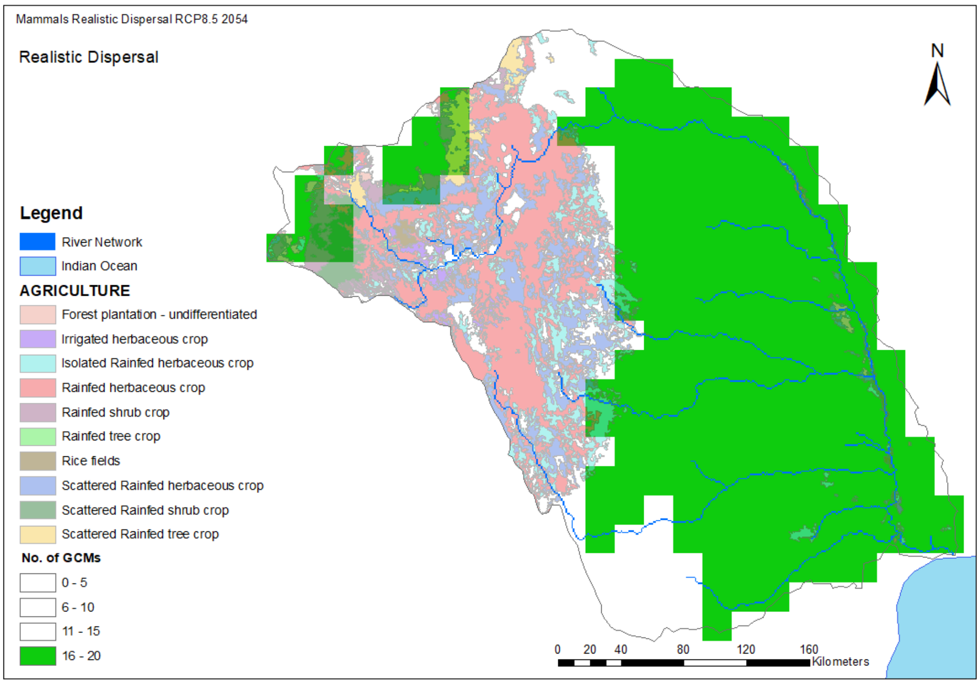

Figure 7-49: Number of GCMs agreeing on the location of refugia for mammals for RCP8.5 by 2054, assuming realistic dispersal, compared to current agriculture within the Tana River Basin

The situation is even more worrying for birds, which have extremely limited refugia in the Tana River Basin assuming no dispersal. This is shown in Figure 7-50. These refugia coincide with existing PAs and some agricultural land in the north of the basin. If birds are allowed to disperse, there are more refugia across the basin. However, many of these still overlap with existing agriculture, as shown in Figure 7-51.

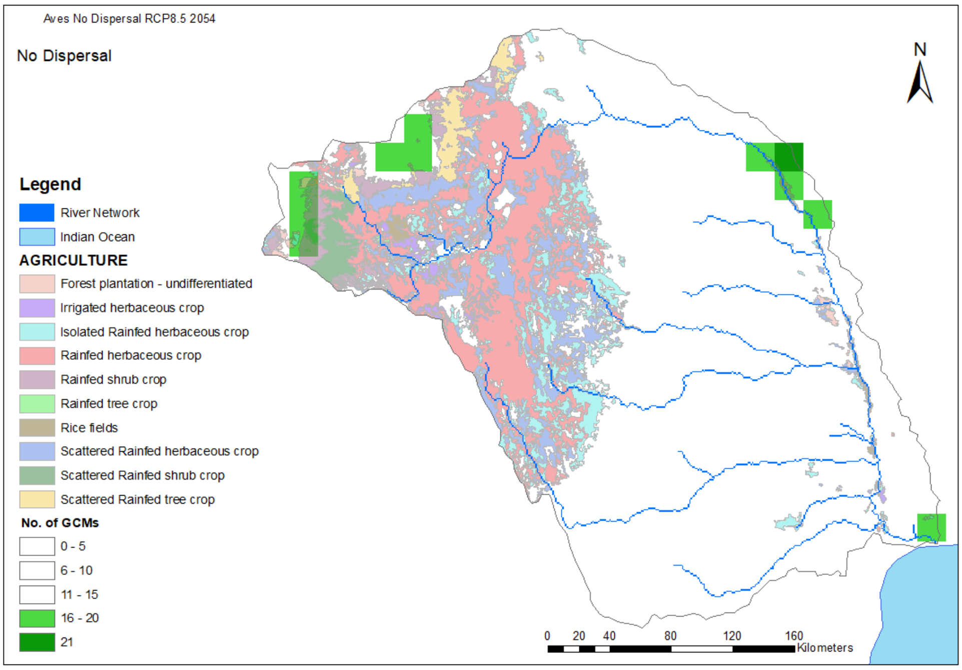

Figure 7-50: Number of GCMs agreeing on the location of refugia for birds for RCP8.5 by 2054, assuming no dispersal, compared to current agriculture within the Tana River Basin

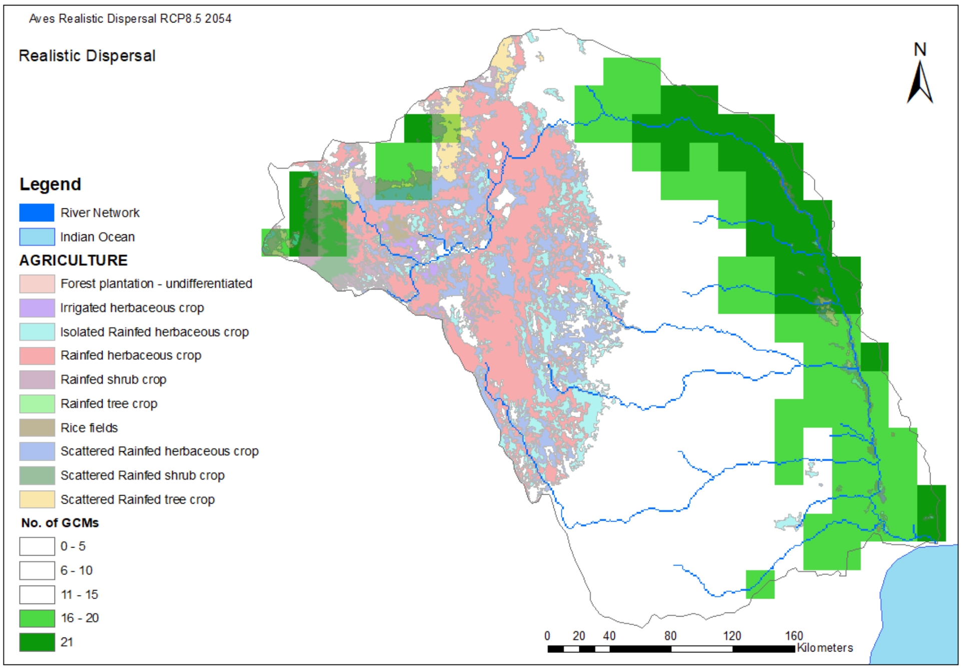

Figure 7-51: Number of GCMs agreeing on the location of refugia for birds for RCP8.5 by 2054, assuming realistic dispersal, compared to current agriculture within the Tana River Basin

7.5.2 Future Agriculture and Biodiversity

Most crops from the ISI-MIP database (Section 7.4.2) and crop species from the Wallace Initiative (Section 7.4.3) have also shown increases in yield or climate suitability in the same area as the refugia in the north of the basin. These upslope areas are likely to maintain cooler conditions relative to most of the basin, so many species will still be able to survive here. However, the land is very limited, so trade-offs between species and land uses is likely.

Furthermore, the areas where the majority of climate and crop models project increases in millet yields overlap with existing and proposed PAs, as shown in Figure 7-52. The new proposed PA based on taxa level results (originally shown in Figure 6-43 and shown with a purple outline on the figure below) overlaps with an area where the majority of the models project increases in millet yields for RCP2.6 without irrigation. The areas covered by the Mount Kenya National Park and the Aberdare National Park in the northwest of the basin are projected to see increases in millet yields under both RCPs and irrigation scenarios.

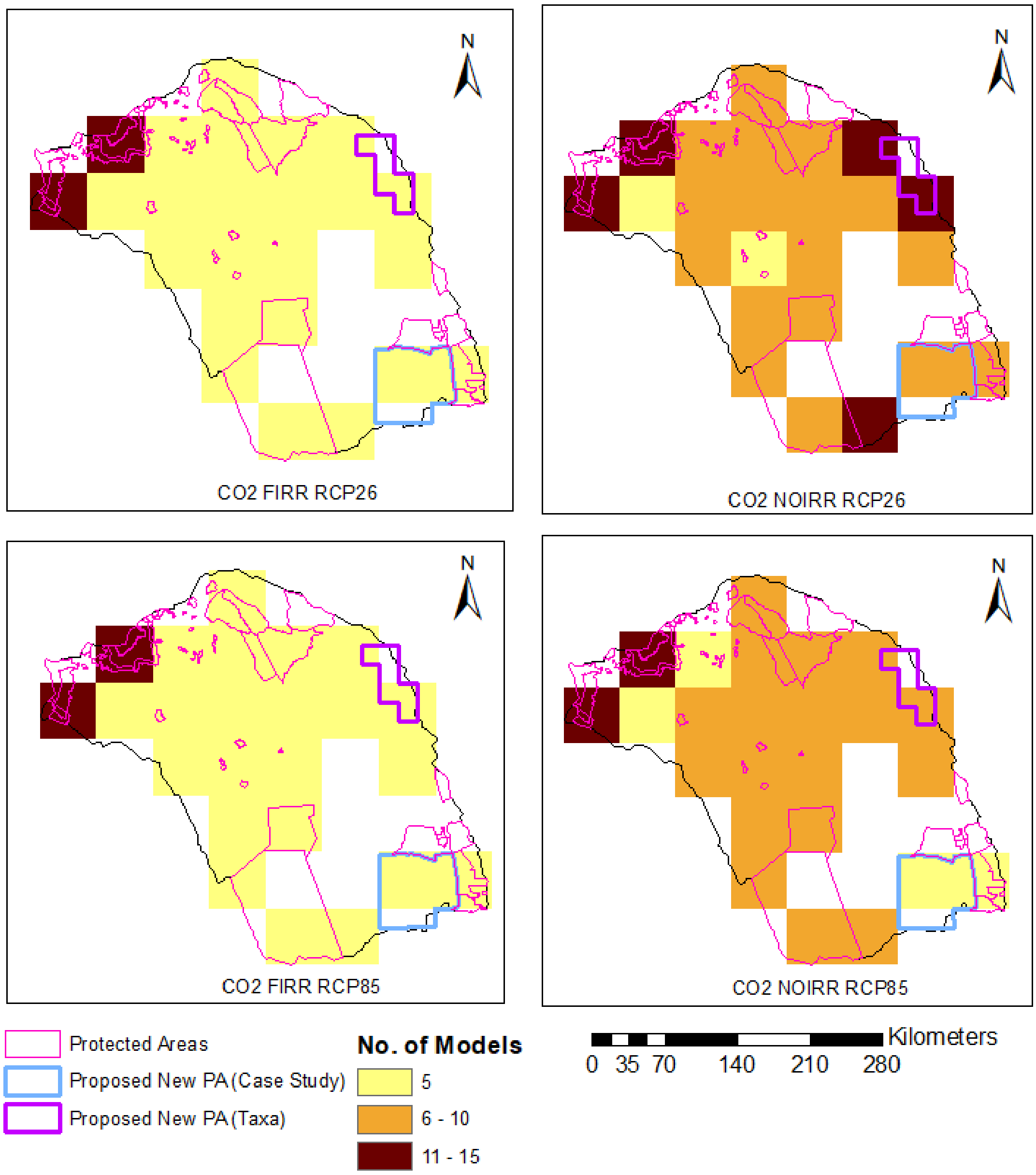

Figure 7-52: Millet yields and existing and proposed PAs within the Tana River Basin

A similar situation is seen for the other ISI-MIP crops. The one cell where most models agree that maize yields will increase under RCP2.6 conditions with full irrigation is already covered by the Mount Kenya National Park. Similarly, this area is also projected to see increases in sugarcane yield for RCP8.5 with and without irrigation. Under RCP2.6, Aberdare National Park area is also projected to see potential increases in sugarcane yields. With wheat, with full irrigation, the cells where the majority of the models project increases in yield are also covered by the Mount Kenya and Aberdare PAs. This suggests that, although increases in yields with climate change may be possible, the land in the optimal areas (with the correct climate conditions) may not be available for cultivation.

7.5.3 Development Plans and Important Biodiversity Areas

Proposed land use changes from the National Spatial Plan (GoK, 2017) will also have implications for wildlife and plants, both in terms of current PA management and potential climate refugia for the different taxa. In terms of the current PA network, some protected areas in the upper Tana Basin may be impacted by the proposals set forward in the National Spatial Plan (GoK, 2017). Figure 7-53 shows the current protected areas overlaid onto the proposed developments for the Upper Tana River Basin. Some proposed irrigation areas overlap with existing PAs, such as Meru National Park. There are also several smaller community reserves and forest reserves in the areas of high- and medium-potential agricultural development. This suggests that the more informal types of PA were not considered during the development of this plan.

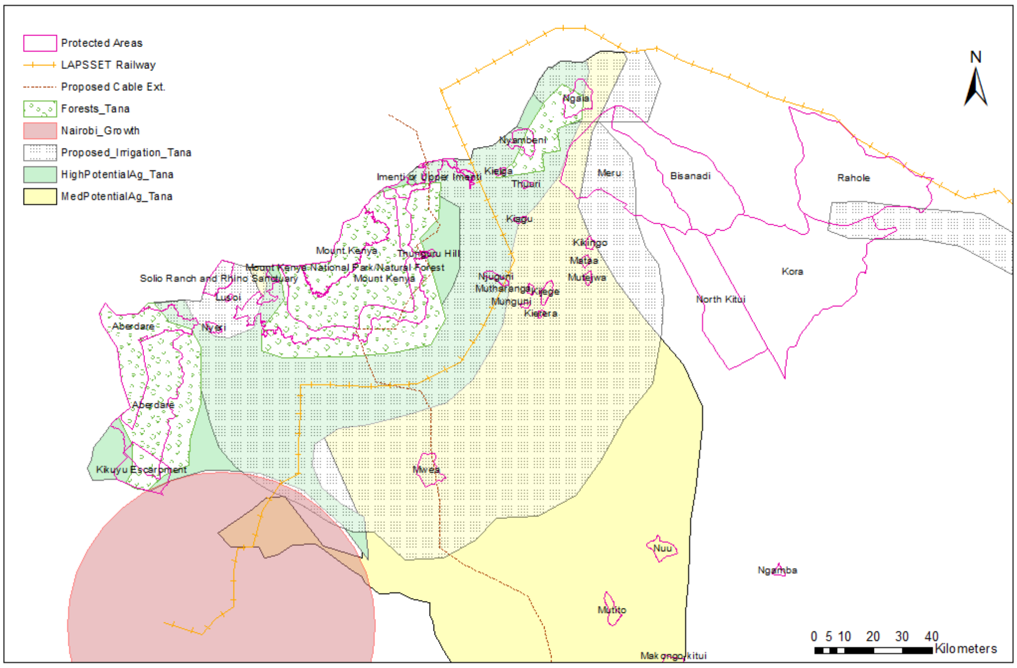

Figure 7-53: Protected Area Network in the Upper Tana Basin compared to the proposed developments

It is possible that these PAs (as tourist hotspots) in the north of the basin will experience some benefits from the National Spatial Plan proposals. New or improved roads and railway lines are planned as part of the LAPSSET corridor project, which may increase the number of visitors to these wildlife areas. However, Figure 7-53 also shows that the LAPSSET railway line is planned to run directly through a cluster of small PAs (forest reserves).

Another area of proposed irrigation runs next to the river in the lower part of the basin, including passing through existing PAs, such as the Lower Tana Delta Conservation Trust and the Hanshak-Nyongoro Community Conservancy.

If these plans are compared to refugia, it is clear that areas set aside for development often coincide with land important for biodiversity. The following figures show the development plans and the areas where 15 or more GCMs identify refugia for the different taxa. Figure 7-54 shows that the majority of plantae refugia overlap with the agricultural development and irrigation proposals. A similar situation is shown for mammals (Figures 7-55 and 7-56) and birds (Figures 7-57 and 7-58).

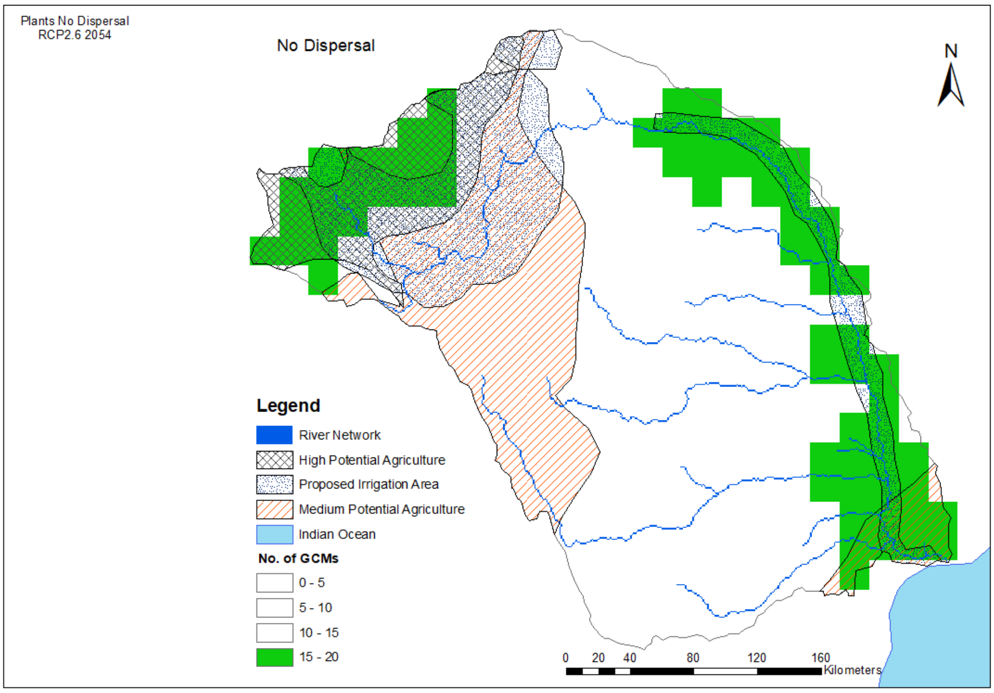

Figure 7-54: Proposed agricultural development compared to the number of GCMs agreeing on the location of refugia for plants for RCP2.6 by 2054 within the Tana River Basin

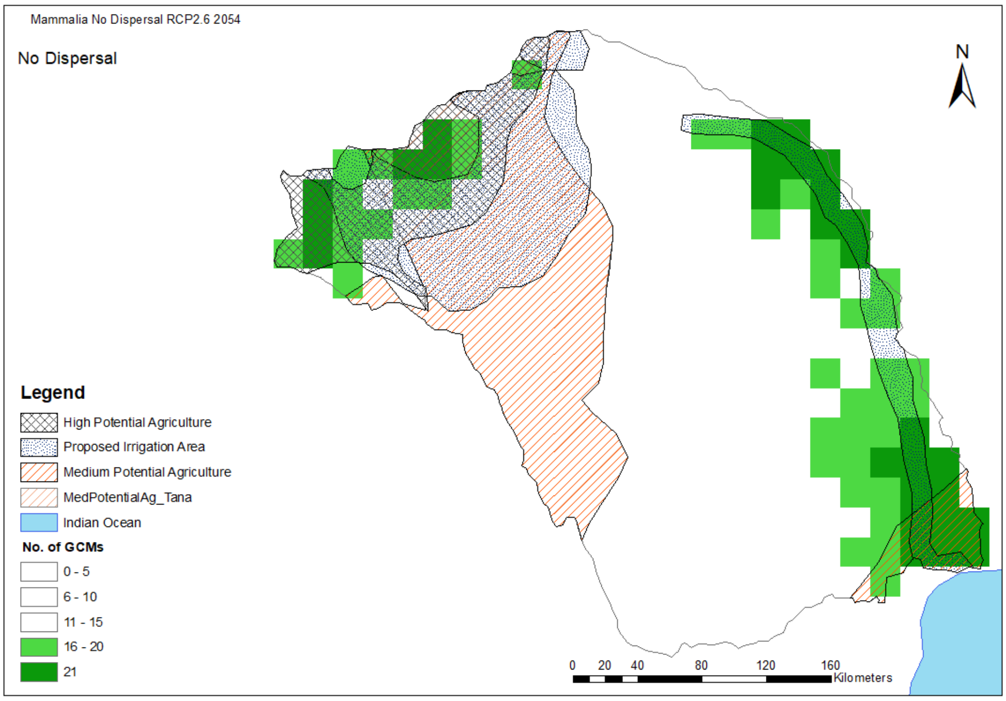

Figure 7-55: Number of GCMs agreeing on the location of refugia for mammals for RCP2.6 by 2054 assuming no dispersal compared to proposed agricultural development within the Tana River Basin

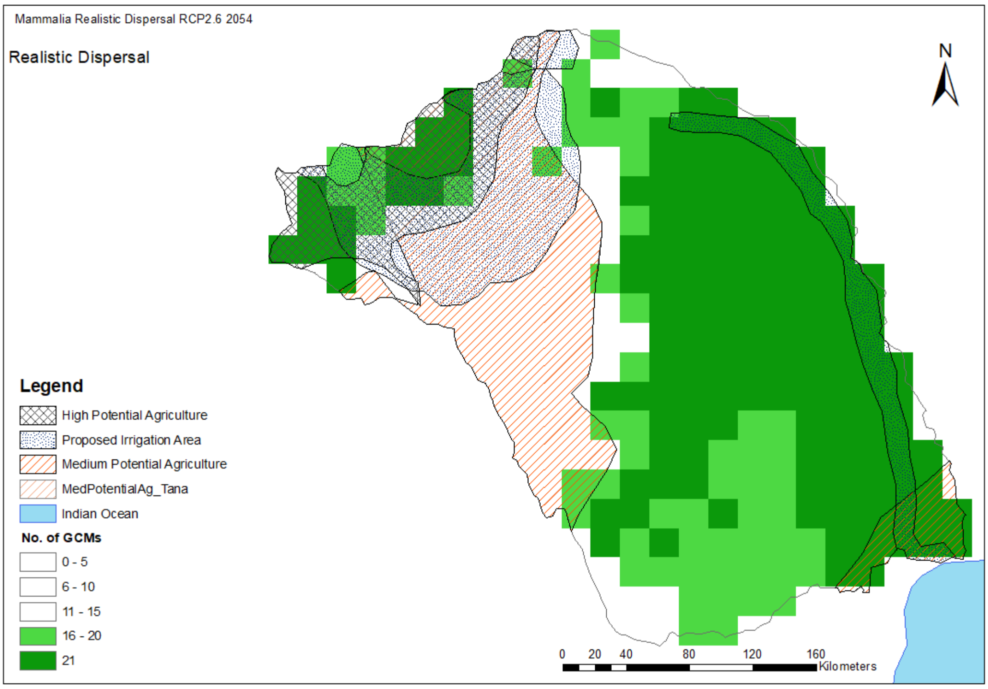

Figure 7-56: Number of GCMs agreeing on the location of refugia for mammals for RCP2.6 by 2054 assuming realistic dispersal compared to proposed agricultural development within the Tana River Basin

The importance of allowing species to disperse through appropriate environments and land covers is demonstrated again here.

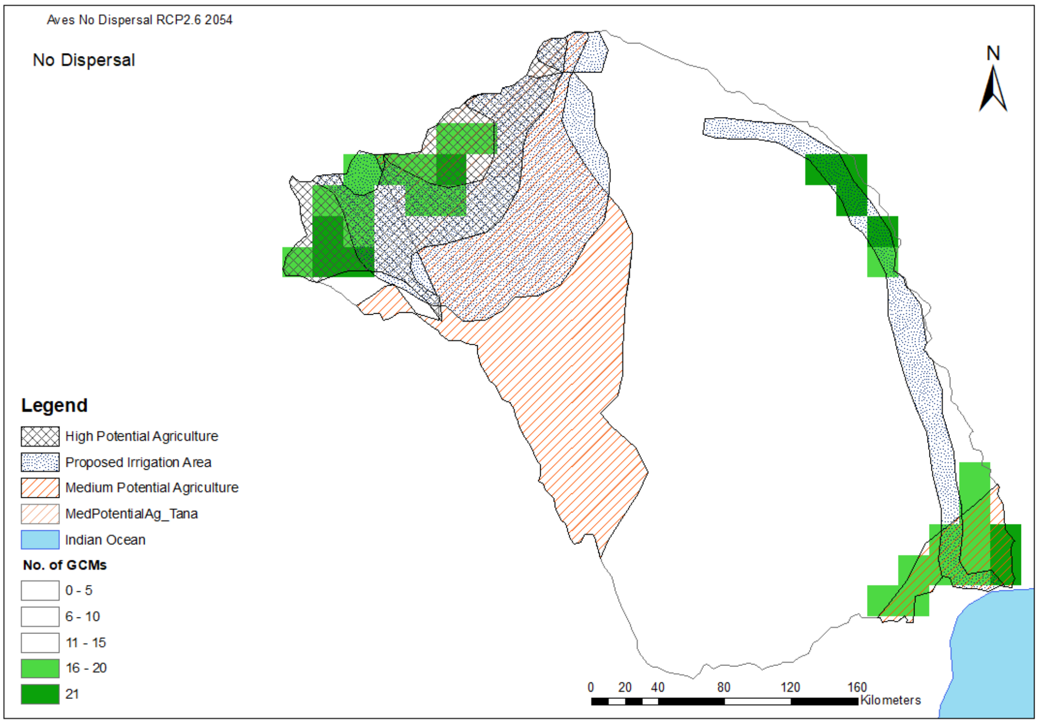

Figure 7-57: Number of GCMs agreeing on the location of refugia for birds for RCP2.6 by 2054 assuming no dispersal compared to proposed agricultural development within the Tana River Basin

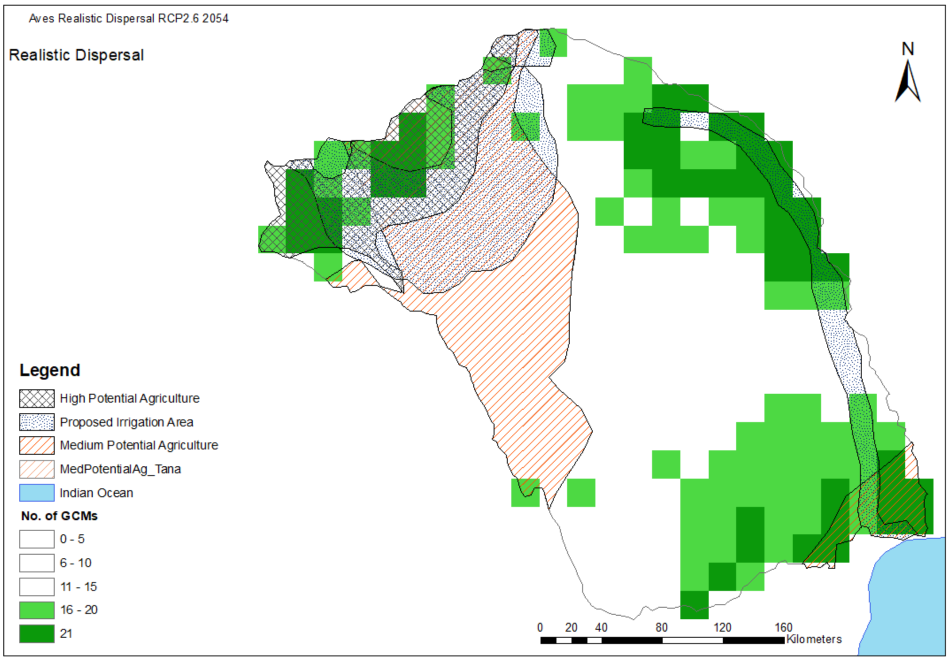

Figure 7-58: Number of GCMs agreeing on the location of refugia for birds for RCP2.6 by 2054 assuming realistic dispersal compared to proposed agricultural development within the Tana River Basin

More refugia for amphibians (Figure 7-59) and reptiles (Figure 7-60) are present so the overlap with proposed agricultural development is not as concerning.

However, the refugia are still concentrated in the highlands and along the main river to the Tana delta.

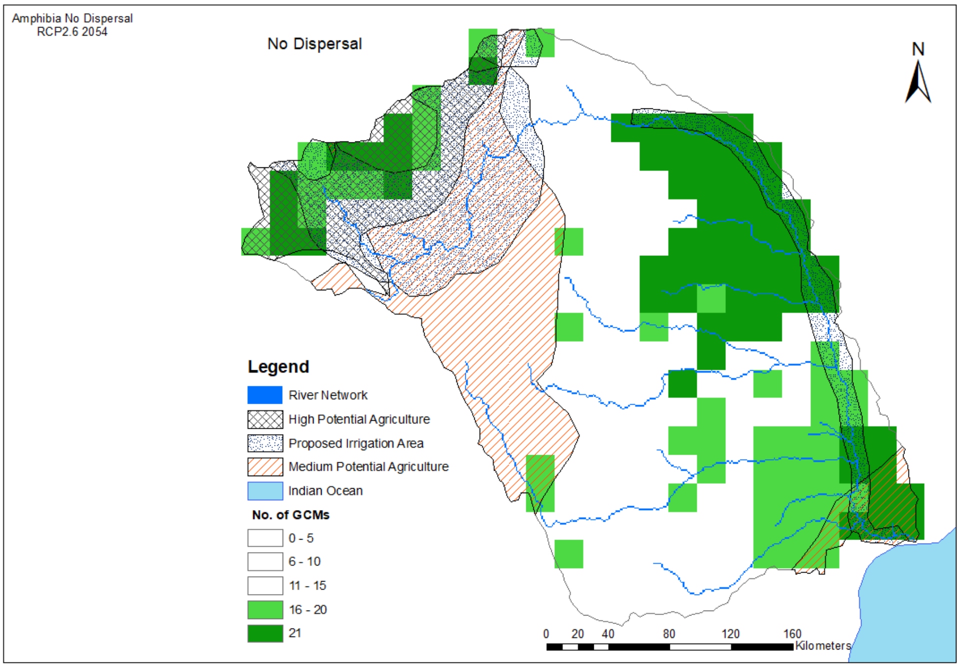

Figure 7-59: Number of GCMs agreeing on the location of refugia for amphibians for RCP2.6 by 2054 assuming no dispersal compared to proposed agricultural development within the Tana River Basin

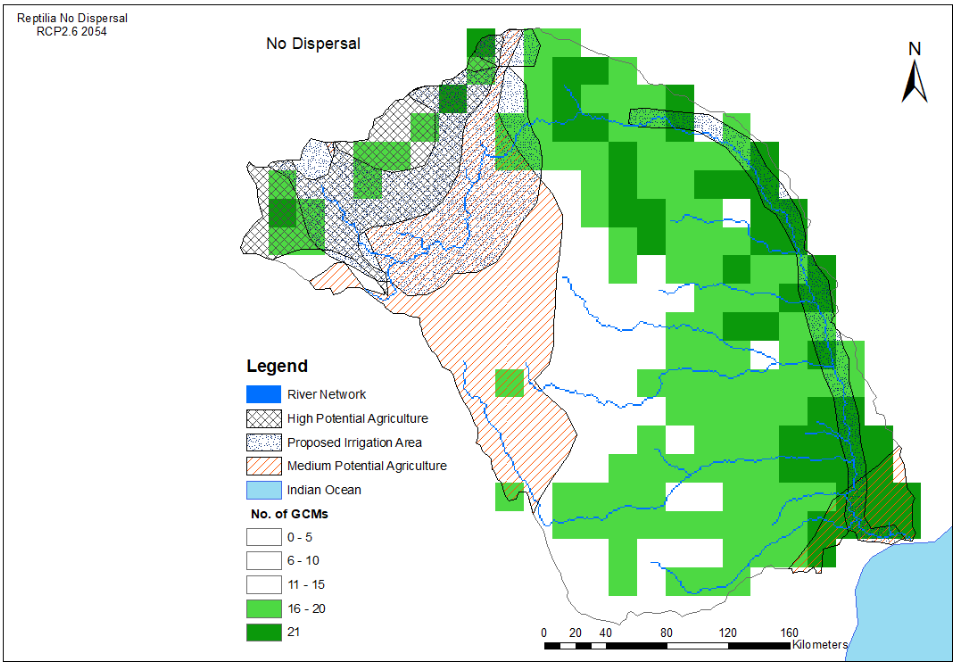

Figure 7-60: Number of GCMs agreeing on the locations of refugia for reptiles for RCP2.6 assuming no dispersal compared to proposed agricultural development within the Tana River Basin

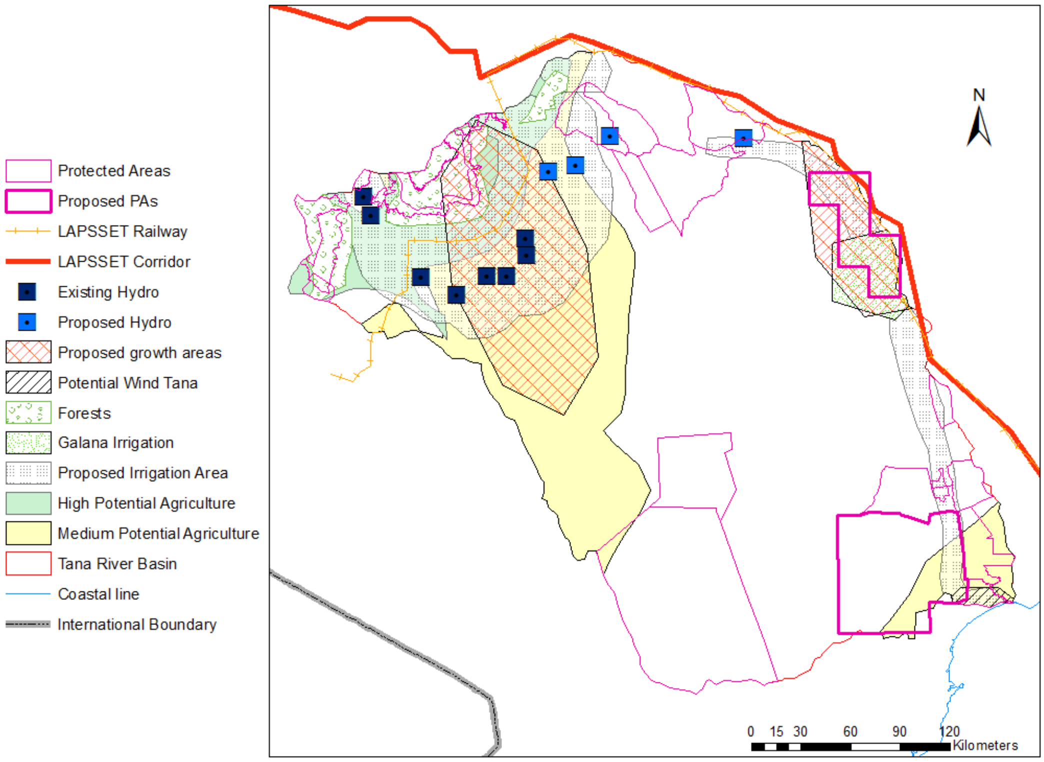

Figure 7-61: Key features of the National Spatial Plan within the Tana River Basin in comparison to current and the proposed new PAs which were identified in Chapter 5.

Figure 7-61 clearly shows that the development projects within the National Spatial Plan overlap with the proposed PAs from Chapter 5 (Figures 6-42 and 6-43). The proposed PA which would cater for the case study species (in the south of the basin) overlaps with proposed irrigation areas, medium potential agricultural land and proposed wind energy development sites. Similarly, the proposed PA which would better protect the animals at the taxa level (east of the basin) overlaps with proposed irrigation areas, including the Galana Irrigation Scheme, and proposed economic growth area.

By examining proposed developments and current agriculture alongside PAs and refugia, it is already apparent that some trade-offs may arise in the north of the basin, as both native plants and animals and agricultural crops move towards these cooler, upslope areas. Agricultural expansion is central to Kenya's National Spatial Plan (GoK, 2017) and Vision 2030 (GoK, 2007). Land of high agricultural potential occurs in the highlands in the north of the basin, which contain important PAs and refugia.

7.5.4 Agriculture and Water Availability

It is important to remember that ISI-MIP only considers 5 GCMs. By examining the WaterWorld outputs for these 5 GCMs, it is clear that each shows a very different pattern of changes to rainfall. Figure 7-62 shows the cells that are projected to become wetter or drier by each of the 5 GCMs. This is beneficial because it shows the ISI-MIP agricultural projections include a range of possible climate futures, but also indicates that substantial differences between the crop projections is likely.

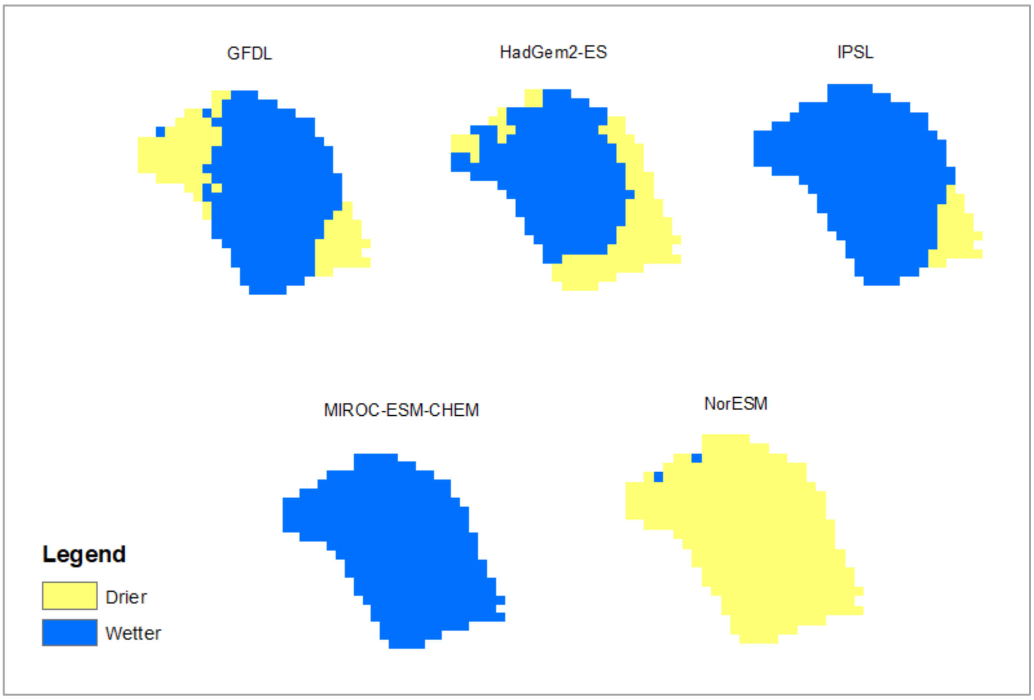

Figure 7-62: Areas of the basin projected to become wetter (blue) or drier (yellow) by the 5 GCMs included in the ISI-MIP database. Data from WaterWorld outputs.

The uncertainties surrounding changes to the hydrology of the basin are central to addressing the questions of potential increases in crop production from additional irrigation (Rosenzweig *et al.*, 2017).

Using the agreement between the GCMs included in WaterWorld shows that the models do not all agree on whether areas proposed for agricultural development will get wetter or drier. The agreement between the 17 GCMs for RCP8.5 compared to the agricultural and irrigation areas is shown in Figure 7-62. Fewer models project wetter conditions in the upland areas and near the Tana Delta at the coast.

These areas are the same areas that suitability for the majority of agricultural species is projected to remain in the future. As there is uncertainty in the hydrological projections in this area, the future of agriculture in this area can also be seen as uncertain. As previously shown, there are many PAs in these regions. The uncertainty over changes to rainfall will also impact the species within these conservation areas.

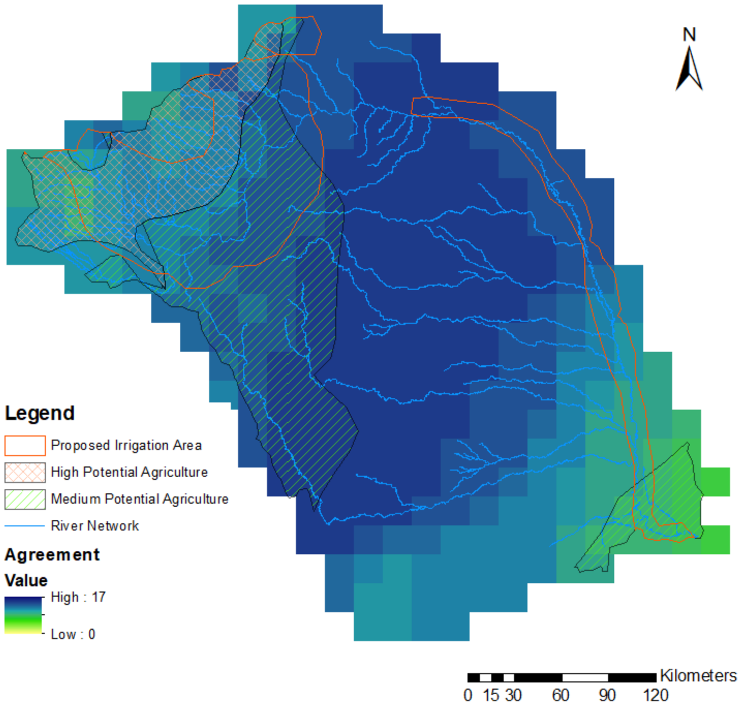

Figure 7-63: Areas of the basin projected to become wetter (darker blue is where more models agree) compared to the proposed agricultural and irrigation areas

The few agricultural species that are suitable for the land in the centre of the basin may fair better, as more GCMs project higher rainfall in this region. However, there are no areas of the basin where all of the GCMs project wetter conditions.

7.5.5 Agriculture and Soil Properties

The soil conditions must be considered alongside the climatic factors for agriculture. There are some areas close to the river in the east of the basin that show moderate and severe constraints to soil workability (originally shown in Figure 7-41). Significantly, this area includes land set aside for increased irrigation, including the area dedicated to the proposed Galana Irrigation scheme, which is shown on Figure 7-64 corresponding to areas of moderate constraints to soil workability. These soil constraints may limit the success of irrigation and agricultural development in this area.

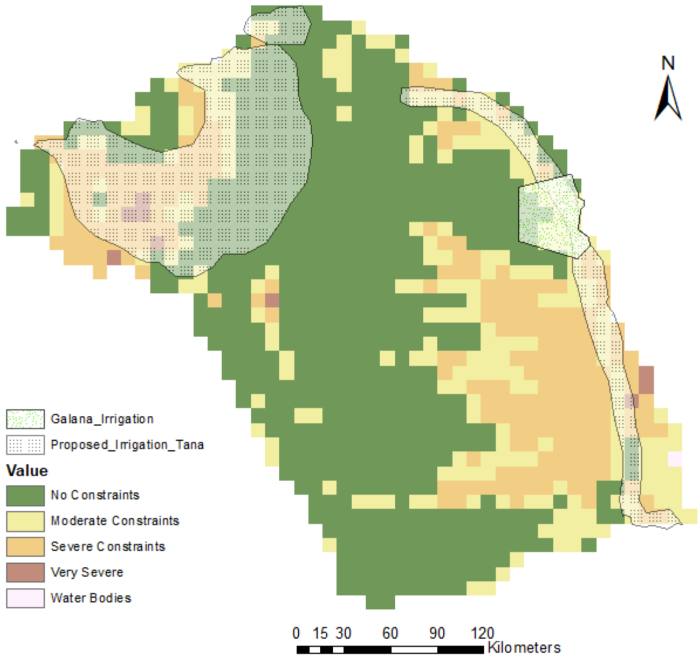

Figure 7-64: Soil conditions compared to the proposed irrigation area and Galana irrigation area

7.5.6 Hotspots of Trade-offs

From this analysis, it is clear that there will be hotspots of conflict between competing land uses within the Tana River Basin. The Upper Tana Basin likely to be an area of trade-offs. As the climate warms, the land further upslope is likely to become more and more suitable for plants and animals. A large range of species will be forced to occupy this smaller space. The Mount Kenya National Park and Natural Forest, Aberdare and the Solio Ranch and Rhino Sanctuary are important PA in the north of the basin that are projected refugia for plants and animals under high levels of warming.

Figure 7-65 shows that a number of smaller PAs may be lost within the larger agriculture and irrigation areas.

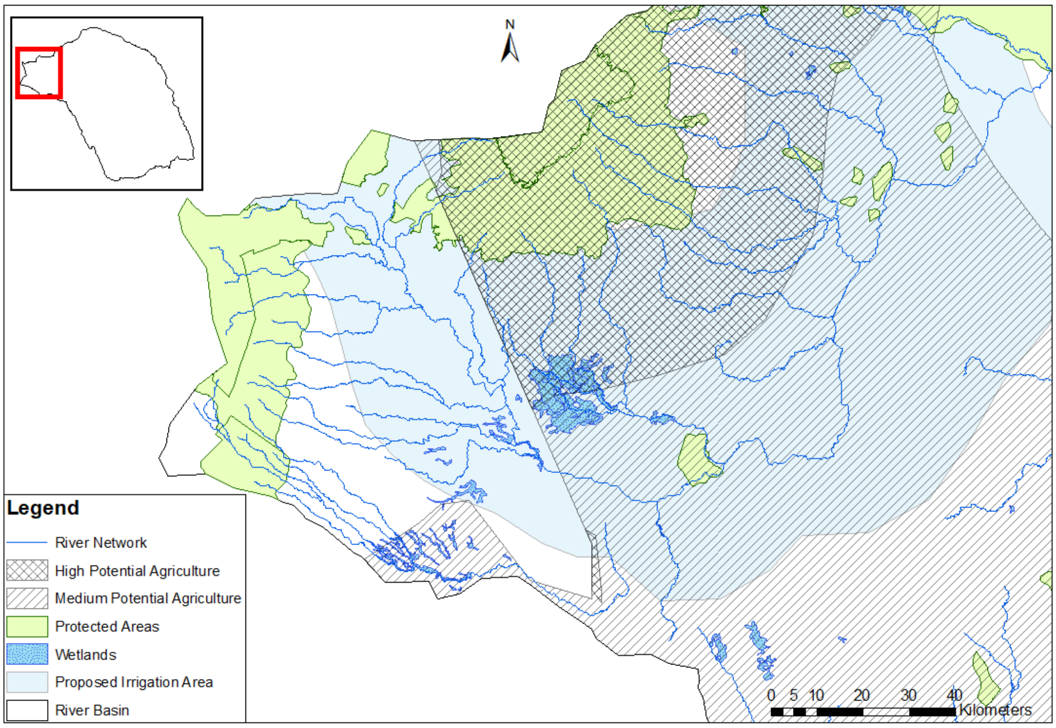

Figure 7-65: Conflicting land uses that may result in trade-offs in the Upper Tana

Another geographical region that may experience trade-offs is the Tana Delta, which is shown in Figure 7-66. The Delta contains sensitive ecosystems, including wetlands and mangroves. The land in the delta has been designated medium-potential for agricultural development by the National Spatial Plan. There are also plans to develop wind energy and construct an airport in this area. In the Delta, the Lower Tana Delta Conservation Trust, Witu Forest Reserve and the Hanshak-Nyongoro Community Conservancy are important PA that are also projected to be refugia for a range of species under high levels of warming. The Tana Delta is also a hotspot for adventure tourism and may see increases in livestock (which was shown in Figure 7-43).

Much of the Tana Delta region is a Ramsar-designed wetland (Ramsar, 2012). In addition, the turtle breeding grounds along the coast form part of a WWF-Kenya project to protect the semi-pristine ecosystems around this section of coastline (Olendo, 2015). Loss of mangrove forests is already a concern in this area.

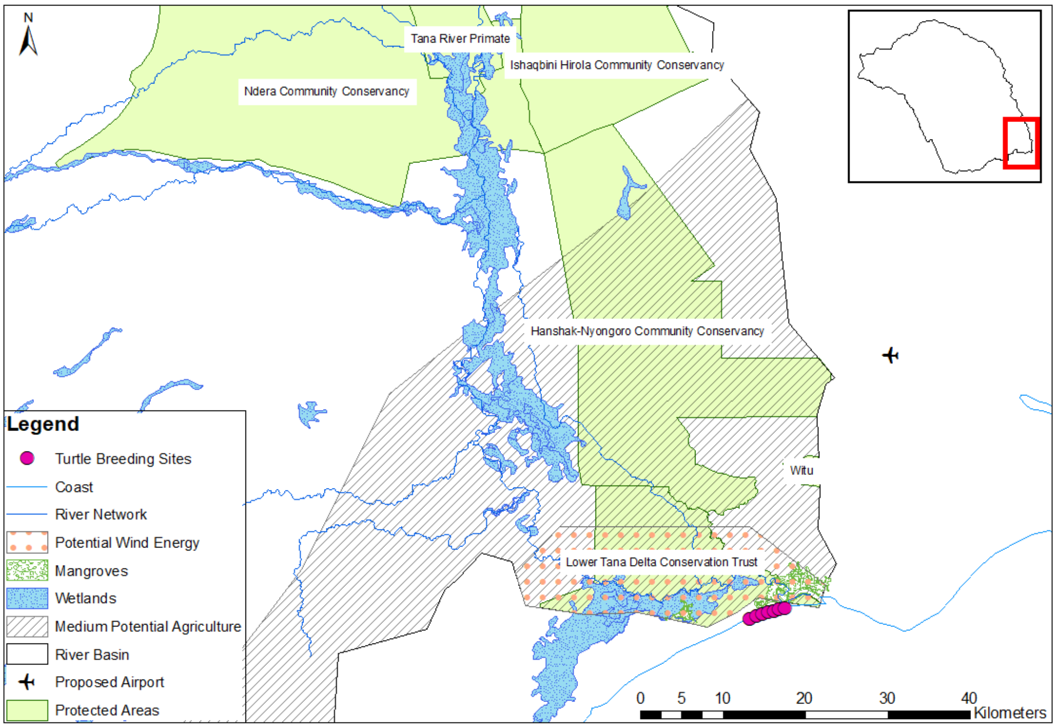

Figure 7-66: Conflicting land uses that may result in trade-offs in the Tana Delta region

7.6 Discussion

Staple crops, such as maize and wheat, may no longer prove viable in some areas, with the total yield for the Tana River Basin area decreasing under most scenarios. Some cells are projected to experience increases in yields under some scenarios but as the sum change is largely negative, these rises are offset by larger declines in other areas. Studies have shown the impacts on agriculture become greater further into the future (Challinor *et al.*, 2014). Areas that experiences increases in yields in the medium time horizon may see reductions in yields with further warming. Yield decreases in tropical regions have been found to be stronger in the second half of the century (Challinor *et al.*, 2014). The IPCC (2014) showed that a moderate increase in global yields occur with up to 3°C of warming; mainly due to the positive effects of CO_2 fertilisation. However, the magnitude of projected impacts on crops varies greatly between studies. This was noted by Muller *et al.* (2017), who showed that the models show the best skill for maize and soybean crops. Schleussner *et al.* (2016) also used the ISI-MIP FT data to analyse changes to crop yields. Their results showed that, for many crops, the differences between the scenarios with CO_2 and without CO_2 effects were larger than the differences between levels of warming. Furthermore, changes to plant nutrient content with higher CO_2 levels may make the situation worse (Medek *et al.*, 2017). Myers *et al.* (2014) show reductions in grain protein content of up to 15% for wheat.

ISI-MIP projections show increases in millet yield in the future. By contrast, the Wallace Initiative database projects a decline in millet suitability in the north of the basin. Two different varieties of millet – finger millet and pearl millet – both show reductions in the suitable climate space using the Wallace Initiative database. The suitable land for both varieties is concentrated in the upper Tana. The number of suitable cells for finger millet decreases from 77 to 68 with 2°C warming and to 54 with 4.5°C warming. This difference could be explained by the fact that the effects of CO_2 fertilisation being absent from the Wallace Initiative data. The small number of projections without CO_2 fertilisation from the ISI-MIP database suggest that total millet yields could reduce.

The Wallace Initiative results show a range of effects on used species distribution. Many of the species recommended for afforestation projects and agroforestry are projected to see decreases in suitability across the basin in the future. One exception is the neem tree. This species is already in increasing demand in Kenya as it is fast-growing and has a number of uses; for instance as a shade tree for plants and animals and as a fuelwood. Assuming the policy that specifies a 10% tree cover on agricultural land is continued, it may become more difficult to achieve as conditions become less suitable for many species. Planting fruit trees, such as mango, may provide a solution, as this species is likely to see an increase in suitable climate space within the Tana River Basin in the future.

Livestock is also an important part of the agricultural system in Africa. The proportions of cells covered by pasture is projected to increase in the future for all LUH2 scenarios. Greater numbers of livestock may lead to further degraded land. Overgrazing has already been identified as a threat to wildlife corridors. This livestock may also be impacted by the changes to plants that are used as fodder.

Higher temperatures may also affect soil fertility and changing rainfall patterns will later soil erosion. Increases in temperature lead to increased turnover rates of organic matter, which leads to a build-up of inorganic nitrogen in the soil (Rounsevell *et al.*, 1999). Drier soils are more easily eroded by the wind and high intensity rainfall events may lead to increased soil erosion in the future. These changes to soil properties are likely to have implications for agriculture.

7.6.1 Implications for the Kenyan people and economy

As agriculture is central to Kenya's economy, all changes to the area suitable for growing will have profound implications for the economy and society. Farmers may need to switch to a different crop. Given that maize crops are already experiencing failures due to drought, those growing maize may find switching to another crop would be beneficial both now and in the future. Decreases in total maize yield are predicted by the majority of models. There are few cells in the basin where over 50% of the models project increases in maize yield and these cells overlap with other important land uses, such as PAs. However, maize is still a staple food in Kenya so the demand for it is likely to continue in the future.

Several strategies have already been proposed in order to deal with the impacts of climate change on maize production in Kenya. International agencies have funded projects into developing more drought-resistant maize varieties, but these may be too expensive for many Kenyan farmers to obtain. In addition, farmers have been encouraged to grow a variety of maize varieties or to diversify into other crops, such as millet or sorghum. However, these more drought-resistant crops do not have a high market value compared to maize. In addition, Rippke *et al.* (2016) found that these more resilient crops may also see reductions in suitability in East Africa in a changing climate. The results of this thesis also show possible reductions in the total yield of sorghum, suggesting that promoting this crop could prove to be maladaptive.

Wheat is gradually becoming more important in the Kenyan diet. As maize prices increase, the poorer sections of the population have replaced maize-based foods with wheat. Rippke *et al.* (2016) showed that both farmers and governments favour transitioning away from maize crops. However, similarly to maize, the models do not agree on where wheat yields will increase in the basin. Many models show a net reduction in wheat yields for the basin. Challinor *et al.* (2014) show that crop-level adaptations are more effective for wheat than for maize systems. This may result in more successful cultivation of wheat than predicted by the models.

The GoK (2017) recognises the potential impact of areas becoming unsuitable for tea production. As the tea industry either directly or indirectly employs 8% of the population of Kenya, reductions in the land suitable for production would severely impact the economy and people. Coffee production is also economically significant so changes in distribution are important to understand. The land suitable for arabica coffee within the Tana River Basin decreases with greater degrees of warming. The remaining suitable area is limited to small areas in the north of the basin. Although land in the west of the basin remains suitable for robusta coffee, Kenyan farmers are unlikely to choose this over the arabica variety as its market value is lower. Furthermore, robusta coffee requires greater irrigation so may not be suitable if precipitation does not increase in the future.

In addition to this, it is important to consider that Kenya has a history of corruption, which has affected the extent to which management and development strategies have been successful. Problems related to land use and biodiversity within the Tana River Basin have been detailed in Chapter 5, Section 2. Complications with the progression of the Vision 2030 have already arisen and are noted by Gainer (2015). These difficulties include a lack of coordination between the different agencies involved with implementing the agenda and that the ministries involved also had other priorities and have not always prioritised projects involved in the Vision 2030. Ongugo *et al.* (2014) argue that the multiple policies and environmental frameworks have led to weak coordination. Overlapping mandates may lead to conflicts between ministries and prevent them from adequately tackling the problems posed by climate change.

7.6.2 Implications for Water Resources

A central consideration is the water use and drought sensitivity of different crops. The water need of crops is determined by a number of factors – the climate, the crop type and the growth stage. Crop water productivity (CWP) is the ratio of crop yield to total water use throughout the development period of the crop. It is defined as yield divided by actual evapotranspiration. A higher CWP means that a crop can produce more with the same volume of water resources or produce the same yield with less water.

Maize and bean crops are known to have a higher sensitivity to drought. This is seen in the results from the common bean, which shows large reductions in the area suitable for growth with higher levels of warming. The IPCC (2014) notes that wheat–based systems are more adaptable than those of maize. Millet and sorghum have greater water efficiency than maize so they may prove better for adapting to climate change in semi-arid environments. Sorghum is classed as a climate-ready crop. Grain legumes, such as the pigeonpea and groundnut, can also survive drought conditions. However, these results have shown large reductions in the land suitable for pigeonpea in the future. Table 7-10 shows crop water productivity estimations for various crops considered in this study, adapted from Brouwer and Heibloem (1986). Sugarcane has an extremely high CWP value and sensitivity to drought. Maize and potato also have high CWP values and a high sensitivity to drought.

Table 7-10: Indicative values of crop water needs and sensitivity to drought. Adapted from Brouwer and Heibloem (1986).

Crop	**Crop Water Need (mm/total growing period)**	**Sensitivity to drought**
Wheat	450-650	low-medium
Bean	300-500	medium-high
Maize	500-800	medium-high
Sorghum/Millet	450-650	low
Sugarcane	1500-2500	high
Potato	500-700	high
Pea	350-500	Medium-high

Proposed hydropower plants along the river are included in the National Spatial Plan (GoK, 2017), but if water resources do not increase in the future, these plants will not be able to function. One of the existing dams on the Tana River has already been decommissioned due to low river levels. This will also have implications for the irrigation potential of the upper Tana. Relying on dams to encourage agricultural and economic development of the area under uncertain climatic conditions could lead to a collapse of the sector. Increasing water storage facilities to cope with years of drought has been considered as an adaptation measure.

Changing agriculture also has implications for water quality. Adding fertiliser to enhance crop productivity may create risks for water quality and fisheries. Rosenzweig *et al.* (2017) identify this as a critical interaction between the agricultural and water sectors.

7.6.3 Implications for Biodiversity

An overview of the implications for biodiversity has already been presented in Sections 7.5.1 and 7.5.2. This section will further discuss these results. It is clear that agricultural expansion and intensification in Kenya will have implications for the country's biodiversity. There are a number of agricultural practices that farmers can employ to increase crop yields; each known to have different effects on biodiversity (Kehoe *et al.*, 2017). The National Spatial Plan (GoK, 2017) aims to increase the area of agricultural land, whereas other agricultural legislation also focuses on the need for improved practises, which allow for more intensive agriculture. Kehoe *et al.* (2017) argue that the greatest threat to biodiversity comes from expansion rather than intensification. Therefore, Kenya's biodiversity could be significantly affected by plans to expand agriculture in the Tana River Basin. Water availability limits the distribution of herbivores in the dry season (Smit, 2011), so the refugia around the Tana River itself are particularly important. It is clear from these findings that areas suitable for agriculture often overlap with existing PAs and climate refugia for a range of species.

Changes to land use and agricultural suitability may have more widespread implications for the network of PAs in the Tana River Basin. Private and community conservancies are important parts of the conservation network in Kenya and are being encouraged by current policies and organisations, including the Status of Conservancies Report (KWCA, 2016). They help maintain connectivity between the more established national parks and national reserves and are supported as a land use under the Wildlife Conservation and Management Act (2013). It might be possible for more private farms to convert to wildlife areas if the economic costs of agriculture begin to outweigh the benefits under future climatic conditions. This may result in an expansion of the PA network, which will benefit the endangered wildlife. By contrast, as the upland areas of the Tana River Basin become more suitable for high-value crops, communities may decide to abandon wildlife conservancies in favour of agriculture. As a lack of funding and management capacity is still a problem for wildlife conservancies (KWCA, 2016), the benefits of turning to agriculture may outweigh those of wildlife conservation. This may lead to PAs, wildlife corridors and even refugia in the north of the basin being converted for agriculture. Even if they remain, the small size of these PAs may limit their effectiveness and, as agriculture develops and the reserves become increasingly isolated through a loss of landscape connectivity, the species present may suffer.

As well as agriculture, wildlife tourism is a key component of the Kenyan economy, so it is important to make sure that PA networks are maintained and that agricultural development is not always given priority.

7.6.4 Adaptation Measures Creating Uncertainty

Gaps in our understanding of future socio-economic development and the adaptive captivity of individual farmers contribute to uncertainty. Adaptation creates uncertainty as we cannot predict what individual farmers will do to adapt to the changes in climate. Adaptive capacity and vulnerability will vary greatly across the region. There are multiple human factors involved with agriculture at the local scale, including choosing the planting and harvesting dates, using modern technology and adding fertiliser. Human dimensions are also involved in the range of possible ways of adapting agriculture to climate change. Some adaptation measures are particularly complex, such as introducing new irrigation systems or breeding drought-resistant varieties of plants. Improving land issues is especially challenging due to the interaction between the multiple biophysical and human factors (Davis, 2016). Vincent (2007) argues that these local factors must be taken in to consideration if adaptation measures are to be successful. For instance, Sanchez (2010) showed that the benefits of high-yielding varieties of cereal crops were not seen in Africa, as they were in Asia and Latin America, due to soil constraints in tropical Africa. A key factor in farmers' ability to cope with climate changes and climate variability is to ensure that they have access to all of the relevant information that will allow them to modify production systems accordingly.

7.6.5 Limitations with ISI-MIP and Crop Modelling

Uncertainties arise from the different assumptions made in the crop model development (White *et al.*, 2011). Gridded crop models make a number of simplifications and assumptions, including sowing dates and crop varieties, as well as homogeneous crop management across large areas (Muller *et al.*, 2017). Recent studies (e.g. Lobell and Asseng, 2017) have argued that using a single impact model or crop model is insufficient for assessing the range of potential impacts and the uncertainties associated with these. An example of these assumptions is the different levels of complexity used to represent CO_2 fertilisation effects between GGCMs. Crop response to elevated CO_2 is a source of uncertainty (Deryng *et al.*, 2014). Furthermore, the role of pests and diseases, as well as extreme weather events, is difficult to represent in crop models (Carter, 2010; Gregory *et al.*, 2009; Soussana *et al.*, 2010). These factors are likely to impact current and future crop yields, but cannot be adequately incorporated into global gridded crop models. Moreover, uncertainties in the data used for calibration of the crop models. Most field experiments that have been conducted took place in the USA or Europe, so little is known about how they may react in African countries. Challinor *et al.* (2018b) argued that a better representation of processes is necessary to improve crop modelling and inform adaptation strategies.

As with all modelling projects, ISI-MIP has limitations. Only 5 GCMs are used, so it is unlikely that the results will fully encompass the range of possible outcomes. McSweeney and Jones (2016) demonstrate this, showing that, for temperature, the range of possible outcomes covered by these five GCMs for the East African region is reasonably high, whereas for precipitation it is lower. Furthermore, limitations with the bias correction method used to downscale the climate data affect the ISI-MIP results (Hempel *et al.*, 2013). This bias correction method has been shown to be less effective in areas where the GCM projects very low precipitation, such as the Middle East and northern coast of Australia. However, this study area is not affected by this problem.

The ISI-MIP project, like most existing crop modelling studies, does not account for all economically-important crops within the study region. Although the results of the Wallace Initiative was used to provide information on additional crops, changes to some high-value crops, like potatoes, were not able to be analysed.

In addition, there are limitations with the GGCMs themselves, which may influence their results and limit their usefulness. The GGCM simulations within the ISI-MIP FT database were not harmonised with a common set of input parameters (Rosenzweig *et al.*, 2014). Key differences between the GGCMs have already been discussed and are also shown in Table AVI-1. The GGCMs differ with respect to estimated evapotranspiration (ET) and crop water demand, as well as the specific CO_2 fertilisation effects included. Furthermore, the number of soil layers, management practises and crop growing seasons vary between the crop models (Rosenzweig *et al.*, 2014). Similarly the lack of calibration (or contrasting calibration techniques) further make it difficult to rank the GGCMs in their overall performance of replicating historical crop yields and therefore assessing changes to future yields (Muller *et al.*, 2017). These differences and assumptions highlight the importance of considering a range of crop models and scenarios.

7.6.6 Limitations with WaterWorld for LUCC

As stated in Section 7.3.1, WaterWorld does not incorporate the climate feedback between land surface vegetation and rainfall generation as, at the time of model development, the process was not well understood. Since the model was developed, significant research has been undertaken into this. Biophysical feedbacks operate locally, but may affect larger-scale atmospheric circulation through heat and moisture advection (Avissar and Werth, 2005). Wu *et al.* (2016) modelled vegetation-climate feedbacks in Africa and found that they can enhance the reductions in rainfall caused by climate change in tropical rainforests. However, understanding of these feedbacks is still incomplete (Mahmood *et al.*, 2014). Including the effects of feedbacks into models may improve the results of future research. More general limitations with the WaterWorld model were already presented in Chapter 5, Section 5.5.5.

7.7 Chapter Summary

This chapter has presented the results of land use and agricultural analyses. Maize and wheat production could decrease, whereas millet yields may rise in the future. The agreement between the different crop models and climate models is not strong in the Tana River Basin, so substantial uncertainty still exists. Changes to other agricultural species, such as cowpeas and beans, will also have repercussions for the Kenyan economy. There is a general trend towards the upland areas in the north of the basin becoming more suitable for both wildlife and crop species. As the temperatures in the basin warm, the species are migrating upwards to the relatively cooler conditions that they are more suited to.

Results from the WaterWorld model suggest that the influence of climate change on water balance will be stronger than the influence of land use change. This demonstrates the value of investigating both of these changes as well as the importance of understanding how climate may be different in the future. Changes to rainfall will have profound effects on agriculture.

By integrating the different results, it is clear that challenges for management and policy will arise. The conflicting land uses in the north of the basin may lead to trade-offs between economic development and species conservation. Similarly, the Tana Delta is likely to experience a lot of pressure from competing user groups. These results confirm the importance of integrating different sectors and aggregating the risks and benefits of future climate change to the Tana River Basin to provide a more holistic assessment.

Chapter 8 Discussion

The results of this thesis contribute to a greater understanding of the impacts of climate change on key sectors in the Tana River Basin, which is an area already under pressure from competing land and water uses. This chapter first summarises the main findings for each sector (Section 8.1) and then provides a discussion of how these sectors are likely to interact (8.2). Then, the policy and management implications of this research are considered in Section 8.4, followed by the strengths (8.5), limitations (8.6) and possible areas for future research (8.7).

8.1 Sectoral Impacts and Adaptation

Climate change is likely to have a significant impact on the Tana River Basin. Projections of basin-average mean annual temperature change range from 1.3°C for RCP2.6 to 2.1°C for RCP8.5 based on the multi-model mean scenarios in the 2050s. This research has examined the potential impact of climate change on the water, biodiversity and agriculture of the Tana River Basin. Table 7-1 shows the key findings of this research. The confidence in these results is expressed qualitatively, based on the same confidence levels used in the IPCC reporting process, which uses agreement and evidence to determine confidence (Stocker *et al.*, 2013). A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high. Figure 8-1 shows summary statements for evidence and agreement and how these relate to confidence. Very low confidence relates to low agreement and limited evidence, whereas very high confidence corresponds to high agreement and robust evidence.

Here, the amount of evidence refers only to evidence obtained through this study. Agreement refers to the consistency in the results of the different models and emissions pathways considered within this study. For example, the statement that refugia are projected to exist for animals in the Upper Tana (see Table 8-1) has been given a ‘very high’ confidence level because it is based on the agreement between 21 GCMs, 4 RCPs and 4 animal taxa, which can be considered robust evidence. By contrast, projected changes to sorghum yields have been given a ‘low’ confidence level. This is because the results are only based on 2 GGCMs (limited evidence) and there is significant variation in the projections (low agreement).

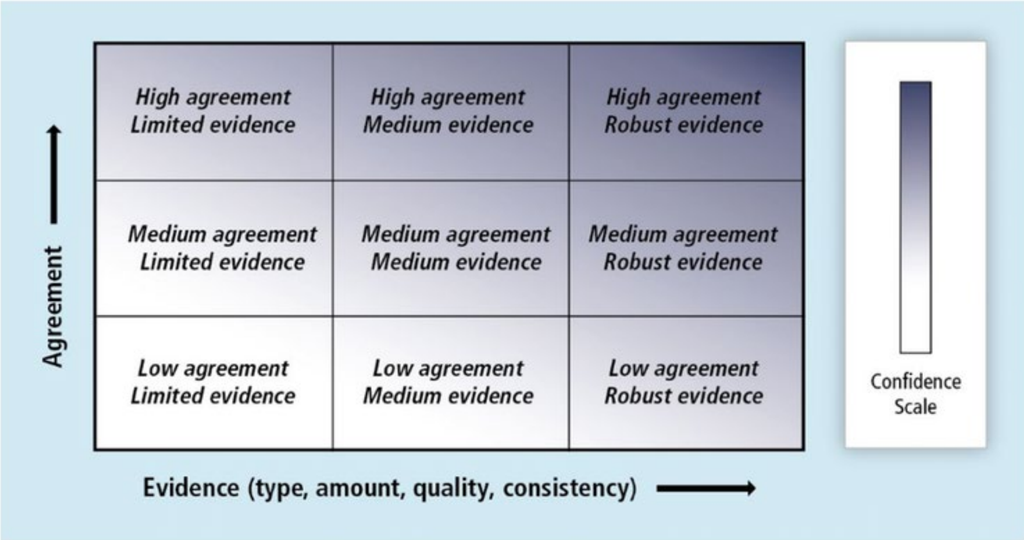

Figure 8-1: A depiction of IPCC evidence and agreement statements and their relationship to confidence. Taken from Stocker et al. (2013). Confidence increases toward the top right corner of the diagram.

This section will further discuss the key findings of this research and the different adaptation options that are appropriate for each sector identified in this research. Section 8.1.6 then provides an overview of the adaptation options that have been identified through this study.

Table 8-1: Key findings of this research

		Present	Future
Hydrology	Precipitation (Chapter 3)	• Rainfall is concentrated in the highlands of the Upper Tana (Section 3.3) • The months of peak rainfall are April and November. (Section 3.3)	• Wetter rainy seasons, drier dry seasons. Annually, this leads to an increase (i.e. the increase in the wets seasons is greater than the reduction in the dry seasons) ***(high confidence)*** *(*Section 3.5)
	AET (Chapter 4)	• AET is lowest in the Upper Tana and higher across the floodplain. (Section 4.3.1) • Seasonal variation in basin-average AET is minor. (Section 4.3.3)	• Increases in basin-average AET **(*very high confidence*)** (Section 4.4.1.1)
	Water Balance (Chapter 4)	• At the annual scale, water balance is positive in the north and west of the basin and negative in the east. (Section 4.3.1) • Basin-average water balance is positive in April, November and December. (Section 4.3.3)	• Increases in water balance throughout the basin. ***(high confidence)*** (Section 4.4.1.2) • Changes are greatest in the north and west of the basin, in the higher elevations. ***(high confidence)*** (Section 4.4.1.2)
	Water Stress (Chapter 4)	• High water stress (up to 65% of demand is unavailable) throughout (Section 4.3.1)	• Average percentage changes are not substantial but small decreases in water stress are projected **(*high confidence*)** (Section 4.4.1.4)
	Runoff (Chapter 4)	• Runoff at the Garissa gauging station is highest in May and November, coinciding with the rainy seasons (Section 4.5.5.1)	• Increases in runoff are projected at Garissa for the rainy seasons, whereas reductions are projected for the dry season (***medium confidence***) (Section 4.4.2.3)
Biodiversity	Animals (taxa) (Chapter 5)	• Highest species richness are seen in the mountains in the Upper Tana, along the main river and at the coast in the Tana Delta. (Section 5.4.1) • Important PAs for conserving these animals under current conditions are: Mount Kenya National	• Increasing risk of biodiversity loss with higher temperatures **(*high confidence*)** (Section 5.4.3) • Allowing animals to move reduces their risk of loss from the area **(*high confidence*)** (Section 5.4.3)

		Park, Aberdare, Lower Tana Delta Conservation Trust and the Hanshak-Nyongoro Community Conservancy. (Section 5.4.1)	• Refugia will exist in the Upper Tana ***(very high confidence)*** (Section 5.4.2) • Some refugia overlap with protected areas, including the Mount Kenya National Park and Lower Tana Delta Conservation Trust ***(very high confidence)*** (Section 5.4.2)
	Plants (taxa) (Chapter 5)	• Highest species richness are seen in the mountains in the Upper Tana and at the coast in the Tana Delta. (Section 5.4.1) • Important PAs for conserving plants under current conditions are found in the Upper Tana. (Section 5.4.1)	• Refugia will exist in the Upper Tana and along the main river in the east of the basin ***(medium confidence)*** (Section 5.4.2.1) • Some refugia overlap with the Mount Kenya National Park protected area (***high confidence***) (Section 5.4.2.2)
	Animals (case study) (Chapter 5)	• Highest species richness is seen in the mountains and in the coastal zones in the south of the basin. The southern basin is home to higher numbers of reptiles and amphibians but much of this land is not covered by the existing protected area network. (Section 5.5.1) • Important PAs for conserving these animals under current conditions are concentrated in the lower basin, such as the Lower Tana Delta Conservation Trust and the Hanshak-Nyongoro Community Conservancy. (Section 5.5.1)	• Increasing risk of species loss from the basin with higher temperatures if movement is restricted ***(very high confidence)*** (Sections 5.5.2-5.5.4) • Allowing animals to move reduces their risk of loss from the area ***(high confidence)*** (Sections 5.5.2-5.5.3) • The PA network may not sufficiently protect the case study animals ***(high confidence)*** (Sections 5.5.6-5.5.7) • Important PAs for conserving these animals in a changing climate include: Hanshak-Nyongoro Community Conservancy, Ishaqbini-Hirola Community Conservancy and Lower Tana Delta Conservation Trust (***high confidence***). (Section 5.5.6)
	Plants (case study) (Chapter 5)	• Highest number of case study plants are found in the southern basin. (Section 5.5.1)	• The majority of case study plants do not see substantial changes in the area suitable within the basin. Some notable exceptions are *Saintpaulia ionantha, Psydrax faulknerae, Pteleopsis tetraptera,*

		• Important PAs for conserving plants under current conditions are also concentrated in the southern basin, such as the Hanshak-Nyongoro Community Conservancy and Tsavo East National Park. (Section 5.5.1)	*Brachylaena huillensis, Cynometra webberi, Gardenia transvenulosa and Dalbergia bracteolata* ***(high confidence)*** (Section 5.5.5) • Hanshak-Nyongoro Community Conservancy and Tsavo East National Park maintain a high number of case study plants with higher temperatures ***(high confidence)*** (Section 5.5.6.4)
Agriculture	Maize (Chapter 6)	• Widely grown across the basin • Highest production is found in the Upper Tana	• Yield reductions in the lower basin and gains are possible within the Upper basin **(*medium confidence*)** (Section 6.4.2.2) • Overall, the total yield within the basin area is projected to decrease **(*low confidence*)** (Section 6.4.2.2)
	Wheat (Chapter 6)	• Production is concentrated in the highlands in the Upper Tana	• Reductions in total wheat yields within the basin (***medium confidence***) (Section 6.4.2.3)
	Sugarcane (Chapter 6)	• Sugarcane yields are highest in the centre of the basin	• Increases in yields could occur in the Upper Tana **(*low confidence*)** (Section 6.4.2.5) • Overall, the total yield within the basin area is projected to increase (***low confidence***) (Section 6.4.2.5)
	Millet (Chapter 6)	• Grown in the eastern basin, apart from the highest elevations	• Total yield within the basin will increase in the future **(*medium confidence*)** (Section 6.4.2.1) • The Upper Tana will produce higher yields in the future **(*medium confidence*)** (Section 6.4.2.1)
	Sorghum (Chapter 6)	• Grown across most of the basin, apart from the highest elevations. • Highest production is in the eastern half of the basin	• Potentially higher yields across the central basin (***low confidence***) (Section 6.4.2.4)

	Other crop species (Chapter 6)	• Economically important tea and coffee regions in the Upper Tana (Section 6.4.3.1) • Widespread suitability for cowpea, pigeonpea and common bean. (Section 6.4.3.1) • West of the basin is suitable for fruit crops such as pineapple, avocado, papaya, tomato and mango. (Section 6.4.3.1)	• The area suitable mango and pineapple will increase ***(high confidence)*** (Section 6.4.3.1) • Contractions in the land suitable tea and coffee growth ***(high confidence)*** (Section 6.4.3.1) • Reductions in land suitable for cowpea, pigeonpea and common beans ***(high confidence)*** (Section 6.4.3.1)
	Reforestation or agroforestry species (Chapter 6)	• Different species suitable for different agroecological zones are found in different areas across the basin. (Section 6.4.3.2)	• *Acacia tortilis, Sesbania sesban* and *Leucaena leucocephala* are particularly sensitive to changes in climate (substantial reductions in the suitable climate space are projected) (***high confidence***) (Section 6.4.3.2) • The neem tree (*Azadirachta indica*) does not show much change in suitable climate space with warming so should be favoured in (re)afforestation projects (***high confidence***) (Section 6.4.3.2)
	Combined land use and climate changes (Chapter 6)		• The combined effects of projected climate and projected land use changes (reforestation) have the potential to partially counteract one another. (***medium confidence***) (Section 6.4.1).

8.1.1 Water

Currently, the highest precipitation volumes, of up to 226 mm/month, occur in the upper Tana, while very limited precipitation occurs across the majority of the mid to lower basin. The basin experiences two rainy seasons: the months of peak rainfall are April and November, while the lowest rainfall occurs between June and August. Annually, the majority of the basin has a negative water balance meaning that losses through evapotranspiration are greater than rainfall inputs into the system. However, the basin-average water balance is positive in April, November and December, when rainfall is greater than AET. Water stress (which is defined as the percentage of the water demand unavailable or contaminated) is high throughout most of the basin.

Chapters 4 and 5 analysed changes to the hydrology of the Tana River Basin with climate change. Most GCMs project wetter annual conditions for the Tana River Basin by the 2050s (Chapter 4, Section 4.2). The basin-average percentage changes in rainfall for the multi-model mean scenarios by the 2050s range from 12 to 16% for RCP2.6 and RCP8.5 respectively. Basin-average annual changes to AET are minor, so the majority of the change in water balance arise from the alterations to rainfall. The basin-average percentage change in water balance is projected to be +31-58% for the multi-model mean scenarios the 2050s (Chapter 5, Section 5).

Increases in rainfall are projected to be highest in the wettest months, while some scenarios lead to reductions in rainfall in the dry season between June and September (Chapter 4, Section 4.2). Increases in evapotranspiration are seen in all months. Although the projected annual increases in rainfall are consistent with previous work on the Tana River Basin (such as Nakaegawa and Wachana (2012) and Sood *et al.* (2017)), the reductions in rainfall in the dry seasons are different from other studies. These previous studies have not considered as many GCMs or RCPs as analysed in this thesis. So, the seasonal difference in the results may arise from this. Therefore, this thesis builds on previous work by considering a greater number of individual projections.

Based on these results, recommendations for adapting the water sector to changes in climate can be identified. The adaptation of water resources to climate change relates to both the supply and demand, as well as the efficiency of the delivery of water to users. Potential reductions in precipitation in the dry months and increases in the rainy seasons may necessitate improvements to water storage. This could involve (re)afforestation to increase evapotranspiration, rainwater harvesting and/or the restoration of wetlands and floodplains. Small-scale rainwater harvesting is already an adaptation method to climate variability in some pastoral communities in Kenya (UNDP, 2010).

By contrast, flooding is a known problem in the rainy seasons and is likely to increase in severity in the future, with higher rainfall projected. Reducing peak flow rate can reduce the effects of river flooding. This could be achieved by altering the main channels of the river network or by increasing vegetation cover in the upper basin to reduce surface runoff. The construction of dams to control and regulate water flow can also reduce downstream flooding and is currently a popular management option in Kenya.

Finally, water demand management should be considered an adaptation strategy. Managing water demand is recognised as an important adaptation method in Kenya's National Adaptation Plan (GoK, 2016). As water from the Tana River Basin supplies Nairobi, managing water demand in Kenya's capital city would be beneficial. This could involve upgrading infrastructure, fitting water efficient equipment and promoting the efficient use of water.

However, it is important to consider the rate at which these changes in climate might occur. If the velocity of the changes is particularly high, there may not be time to fully prepare for the impacts, for instance, building sufficient water storage infrastructure. Similarly, the behavioural change required to alter water demand is likely to take a long time to fully achieve.

8.1.2 Biodiversity

Currently, the highest numbers of species are found in the Upper Tana and around the Tana Delta in the southeast of the basin. The results in Chapter 6 showed that climate change poses a significant risk to the biodiversity of the Tana River Basin. Large reductions in species richness within the basin are possible for all taxa with climate change. For RCP2.6, a basin-average of 67% of mammals, 60% of birds, 74% of plants, 76% of reptiles and 72% of amphibians remain by the 2050s with no dispersal. For higher RCPs, the losses in species richness are even higher. Range loss and reductions in species richness as a result of climate change was previously found by global-scale studies, such as Warren *et al.* (2013a). The case study of individual species (Chapter 5, Section 5) has further demonstrated the potential losses to biodiversity with climate change. Most of case study species are negatively affected by climate change.

Potential climate refugia exist within the Tana River Basin for all taxa. These tend to be centred on the mountains and the Tana delta region. Some refugia overlap with existing PAs. Hanshak-Nyongoro Community Conservancy, Ishaqbini Hirola Community Conservancy, the Lower Tana Delta Conservation Trust and Ndera Community Conservancy were shown to be refugia for animals at the taxa level. With the highest levels of warming, only the Mount Kenya National Park and Forest contain refugia for plants at the taxa level. Identifying which PAs overlap with refugia could show which areas should be the focus of conservation resources.

There are clear benefits of both mitigation (limiting warming) and adaptation (allowing species to disperse). The ‘realistic dispersal’ scenario projects a greater proportion of species will remain in the Tana River Basin with higher temperatures. A basin-average of 79-83% (across the RCPs) of birds remain with realistic dispersal rates. For mammals, around 95% of mammals are projected to remain in the basin when dispersal is included. Similarly, with the case study species, allowing dispersal increases the number of suitable cells for some near threatened (NT) and least concern (LC) category mammals and birds. Constraining warming allows more species to continue inhabiting areas that are already (currently) suitable. The benefits of limiting warming for biodiversity protection and allowing species to move across the landscape was also found by Warren *et al.* (2018a; 2018b).

Based on these results, various recommendations can be determined. First, improving the connectivity of the PAs would be extremely important to facilitate species’ movement. Maintaining or improving corridors is generally considered to be a better adaptation choice than other options, such as assisted colonisation (also known as managed relocation). Wildlife corridors are seen as lower risk and reduce the possibility of invasive species problems (Krosby *et al.*, 2010). However, if corridors are not sufficient or if the rate of warming is too fast for species to keep up, assisted colonisation may become necessary to preserve some species.

Creating new PAs in the south and east of the basin would benefit biodiversity. New PAs could host a larger number of species and could act as stepping stones between the existing PAs in the Delta region and the Tsavo East National Park. Similarly, enlarging some of the smallest PAs, such as the forest reserves in the central basin, may help conserve biodiversity. Extremely small PAs are unlikely to maintain sufficient genetic diversity to fully protect the species within them.

Furthermore, the biodiversity of the Tana River Basin would benefit from the better regulation of the PAs both now and in the future. There are still problems of deforestation and livestock within the PAs (Hamerlynck *et al.*, 2010; WWF Kenya, 2018). In practice, biodiversity conservation and adaptation is likely to involve a range of these measures, which are known as integrated conservation strategies.

The rate of climate warming will also have implications for biodiversity. If temperature thresholds are crossed early, few species will have the time to disperse. If natural dispersal does not occur at a sufficient rate, wildlife corridors may not be effective in preserving the species (Pearson and Dawson, 2005). In addition, decision-makers will have less time to facilitate movement, for example by expanding PAs or developing corridors (Warren *et al.*, 2018a). However, Lavergne *et al.* (2010) have shown that there is increasing evidence that evolutionary changes in some species can occur quickly.

8.1.3 Agriculture

Agriculture within the Tana River Basin is at risk of being negatively affected by climate change, but some positive consequences may also arise. The results of Chapter 6 showed variations between the individual crop and climate models are shown to be substantial, with some projecting yield increases for the major crops and others projecting decreases. The magnitude of projected changes in yields also varied greatly. This has also been noted in previous studies (e.g. Challinor *et al.*, 2007). In addition, there is significant spatial variation in sign and magnitude of yield changes across the basin.

Changes to maize yields are likely with higher temperatures. With full irrigation, most models project decreases in maize yields, with greater reductions for RCP8.5 than RCP2.6. With no irrigation and CO_2 effects included in the simulations, some models project increases in total maize yields within the basin. By contrast, when CO_2 fertilisation is not considered, maize yields are projected to reduce. Again, the reductions are greater for RCP8.5 than RCP2.6. As discussed in the Literature Review, changes to maize with higher temperatures has been fairly widely studied (Liu *et al.*, 2008; Nelson *et al.*, 2009; Schlenker and Roberts, 2009; Thornton *et al.*,

2010) and there is a general consensus that maize yields will decrease in East Africa as the climate changes (Adhikari *et al.*, 2015). However, previous studies have also noted the potential for maize to do well at high elevation locations in Africa (Niang *et al.*, 2014). These potential increases in yields were clearly visible in the results of Chapter 7, Section 4.2.

Millet yields are generally projected to increase with climate change. When no irrigation is included in the simulations but the effects of CO_2 fertilisation are included, the majority of models project small increases in the total millet yield within the basin under both RCP2.6 and RCP8.5. The greatest agreement between the climate and crops models is seen in the upper Tana.

The situation is less clear for sorghum. There is greater agreement over the sign of yield change for RCP2.6 than RCP8.5, but under both RCPs there is uncertainty in the projections for this crop. Fewer individual crop and climate model projections were available for this crop.

Wheat is also likely to be significantly affected. When CO_2 effects are not included, all scenarios project reductions in total wheat yields within the basin. There is greater uncertainty on the sign of yield change when CO_2 effects are included, but many models still project reductions in total wheat yield. There are individual cells in the Central Highlands in the Upper Tana where the majority of models project increases in yield. Wheat has a lower optimum temperature than maize, millet and sorghum (Liu *et al.*, 2008) which goes some way to explaining the projected reductions in yields within the basin. Wheat can be considered one of the most sensitive crops to climate change (Liu *et al.* 2008; Ringler *et al.*, 2010).

For sugarcane, there is a very large variation in projected changes between the individual models. The majority of models project increases in total sugarcane yield within the basin but disagree on the magnitude of the changes. Greater increases are projected when CO_2 effects are included. Adhikari *et al.* (2015) reviewed previous studies and found that overall sugarcane is more resilient to temperature rise than other crops but is particularly vulnerable to rainfall variability.

Data on other crop species were obtained from the Wallace Initiative database and presented in Chapter 7, Section 4.3. Reductions in the area suitable for many crops, including tea, coffee, tomato, cowpea, pigeonpea and beans, were projected. By contrast, increases in the area that is climatically suitable within the Tana River Basin were projected for mango and pineapple.

Based on these results, recommendations for adapting agriculture in the Tana River Basin to climate change would include planting a variety of crops, developing efficient irrigation systems and rainwater harvesting and storage. For agriculture, the scale of adaptation measures varies from the field through farm to basin level. The development and implementation of resilient crop varieties could be pursued to help meet food production requirements. Developing new crop varieties can contribute to climate change adaptation through more efficient water use (Ceccarelli *et al.*, 2007), increased drought-resistance (Smith *et al.*, 2012) and increased ability to cope with nutrient limitations (Sylvester-Bradley and Kindred, 2009).

Diversifying, possibly into non-traditional crop types, may increase the resilience of the agricultural sector. Planting a diverse range of crops would be beneficial due to uncertainties in projections of changes in crop yield (Baker *et al.*, 2015). Traditionally, there is a low crop diversity within Kenyan farms, with most only having one or two crops per plot (World Resources Institute, 2007). Including some more drought-resistant crops in planting may alleviate pressure if the projected increases in rainfall in the rainy seasons do not occur as expected. The results for mango and pineapple suggest that these crops would be useful additional food crop species in a changing climate. In other East African countries, bananas are being planted alongside coffee plants to diversify the crop types and improve the soil quality for the coffee plants (Jassogne *et al.*, 2013). However, McCord *et al.* (2015) show that the decision to diversify crops is particularly challenging for small-scale farmers in semi-arid systems due to the greater variability in rainfall.

Moreover, specific crop management options (e.g. changes in sowing dates) also may help in reducing the negative responses to climate change. There is already evidence of farmers in Kenya responding to climate variability through early planting (Stefanovic *et al.*, 2017).

As the majority of current cropland is rain-fed (Baker *et al.*, 2015), development of small-scale irrigation would be a valuable step in ensuring future food security. Irrigation is already an important strategy to defend against drought and improve agricultural yields in other parts of the world (Wu *et al.*, 2011) and is frequently promoted to help ensure food security in Africa in the future (Adhikari *et al.*, 2015). However, the affordability of irrigation for farmers remains a key problem. Ngigi (2003) showed that irrigation schemes in Africa have proven to be expensive and unsustainable. Agriculture is the main source of livelihoods for the poorest sections of the population in Kenya (Alila and Atieno, 2006). Therefore, rainwater harvesting and storage (discussed in Section 8.1.1) is another important adaptation measure.

Increasing the provision of shade on agricultural land is also an important adaptation measure. This has been shown to reduce heat stress in both crops and livestock. Natural sources of shade, such as trees, have been found to be more effective in reducing temperatures compared to artificial shelters (Bray *et al.*, 1994). Fruit trees are already used to provide shade and to diversify household incomes in Bangladesh (Selvaraju and Sobbiah, 2006).

In addition, it is important to reflect on the speed of the warming. Previous studies have projected serious negative impacts on agricultural productivity in Africa in as little as two decades' time (Easterling *et al.*, 2007; Lobell *et al.*, 2008). Burke *et al.* (2009) found that the for many African countries, by the 2050s, the growing season temperatures will be markedly different from current conditions; with around half of the future growing season being outside of the current temperature range. Furthermore, Challinor *et al.* (2016) argued that warming is already occurring at too fast a rate to develop resilient crop types, which may limit the usefulness of this potential adaptation option. Developing crop types requires lead times of 15 years or more (Chapman *et al.*, 2012; Rippke *et al.*, 2016). Therefore, if this adaptation method is chosen, it should be prioritised.

8.1.4 Afforestation and Agroforestry

Reductions in the area suitable for many of the species that are being promoted for (re)afforestation projects are likely with climate change, as shown in Chapter 6, Section 6.4.4.2. Therefore, the GoK goal of increasing forest cover and species diversity with (re)afforestation projects may not be achieved. Some species are less sensitive to climate changes, such as the neem tree, sycamore fig and wild date palm. Based on these results, these three species are recommended for restoration projects. In addition, as discussed in Section 7.1.3, mango trees may be a useful alternative due to their projected increased suitability in the future.

Other additional tree species with less sensitivity to the changing climate should also be determined and used in these projects.

8.1.5 Land-Use Change and Implications

The results presented in Chapter 6, Section 4.1 have shown that the impacts of climate change on the hydrological variables are greater than the impacts of land use change. Both land use and climate change can result in changes in the water balance, but the magnitude of changes are much greater for climate change. Other recent studies have also found that the impacts of climate change on river basins are greater than the impacts of land use change (Hejazi and Moglen, 2008; Khoi and Suetsugi, 2014). The results of this analysis showed that the impacts of climate change alone were greater than the combined impacts of projected land use and climate change. This suggests that some land use changes have the potential to offset the effects of climate change to some extent. An example of this is afforestation increasing water uptake and evapotranspiration and diminishing the effects of the projected higher rainfall. Much of the existing literature on the combined effects of climate and land use change on water resources considers negative effects, such as reductions in water availability as a result of climate change and deforestation. Here, the changes analysed are very different (i.e. projected increased water availability, reforestation), so it is inappropriate to compare the results to many previous studies. Khoi and Suetsugi (2014) found that the separate impacts of land use change and climate change in a river basin in Vietnam offset each other (i.e. increases in flow caused by climate change are offset by reductions caused by land use change).

8.1.6 Overview of Possible Adaptation Measures

Figure 8-2 provides an overview of the main adaptation options that have emerged from this study for each livelihood zone within the Tana River Basin. These livelihood zones were shown in Figure 1-5, but for this analysis, some similar zones have been combined (i.e. the two coastal zones and the three pastoral zones).

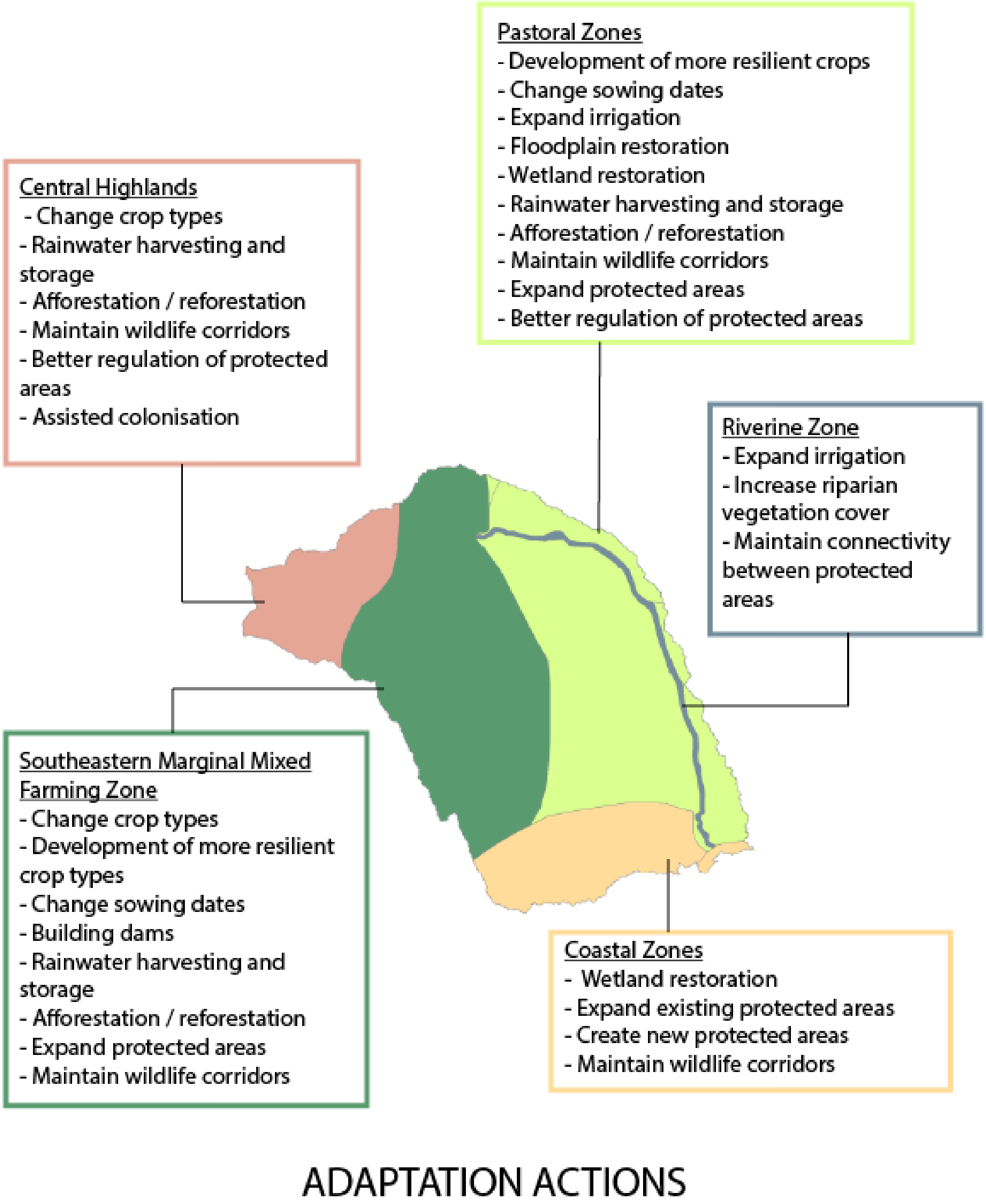

Figure 8-2: Adaptation Actions recommended for each livelihood zone emerging from this study. GIS shapefile livelihood zones data source: Famine Early Warning Systems Network (FEWSNET, 2011) .

It is important to remember that adaptation is a continuous process. Different interventions are likely to be appropriate in various ways at different times and in different combinations. Adger *et al.* (2005) demonstrated the importance of ensuring that short term adaptation options do not prevent or hinder longer term measures.

8.1.7 Other Adaptation Options

The adaptation options identified above were identified from the government reports and from the results of the modelling studies contained within this thesis. However, other adaptation options are available. As fertiliser use results in nitrous oxide (N_2O) emissions, which exacerbates climate change (Gerber *et al.*, 2016), it is not considered here.

As noted in Chapter 3, large-scale crop modelling studies do not often consider on-farm adaptation strategies (Beveridge *et al.*, 2018). Beveridge *et al.* (2018) identified 11 on-farm adaptation strategies which are not included in the modelling studies but were identified through place-based research. These were: building shelters or windbreaks, changing crop, conservation agriculture, crop diversification, crop insurance, fruit tree planting, honey production, livelihood diversification, livestock, seed exchange, shade management and water harvesting. Some of these adaptation strategies have already been identified and discussed in this study (i.e. changing crop, crop diversification, livestock, fruit tree planting, shade management and water harvesting). Crop insurance and seed exchange initiatives are still relatively new in Kenya and uptake varies between regions because of barriers to access and problems with the schemes themselves (such as crops being undervalued) (Oxford Business Group, 2018). Similarly, although honey production has recently been proposed as an adaptation strategy in Kenya, there remain problems with this, including environmental degradation and low honey yields (Carroll and Kinsella, 2013).

8.2 Interactions between and within sectors and adaptation measures

The final part of this thesis focused on identifying cross-sectoral interactions. These interactions can be neutral, positive (synergies), negative (trade-offs) or mixed (Berry and Paterson, 2010). Understanding interconnecting, cross-sectoral impacts is a vital step for developing and strengthening policies focusing on the sustainable use of water and land resources (Maeda *et al.*, 2011).

Based on the recommendations for each sector, trade-offs and synergies within and between adaptation measures and sectors are likely in the future. Tables 8-2 to 8-6 summarise the main interactions between the adaptation options which have been identified in Section 8.1. The synergies are in black and the possible trade-offs are in red. Each table corresponds to a different livelihood zone within the Tana River Basin (which were shown in Figure 1-5 in the introductory chapter).

Each trade-off and synergy is then discussed in sections 8.2.1 and 8.2.2 respectively.

Mitigation was not the main focus of this study, but a few explicit examples of trade-offs and synergises between adaptation and mitigation were found.

Table 8-2: Central Highlands: Adaptation actions and their interactions with other sectors. Positive interactions are in black and negative interactions are in red. Blank boxes indicate that no interactions were identified.

Central Highlands					
	Adaptation Action	**Interacting Sector**			
		Water	**Biodiversity**	**Agriculture**	**Other**
Agriculture	Change crop types			Possible reduction in production of economically or socially important crops.	
	Rainwater harvesting and storage				
Water	Afforestation/ Reforestation	Reduced river flow in rainy seasons Reduced river flow in dry seasons Restore water quality	Habitat change Improve diversity	Possible loss of agricultural land Shade trees on farmland	Mitigation: carbon sequestration
Biodiversity	Maintain wildlife corridors				
	Better regulation in the protected areas				Mitigation: reducing tree loss from PAs could reduce emissions from deforestation
	Assisted colonisation		Could lead to pests in new areas Could endanger other species in the new areas	Could lead to pests	

Table 8-3: South-eastern marginal mixed farming zone. Adaptation actions and their interactions. Positive interactions are in black and negative interactions in red. Blank boxes indicate that no interactions were identified.

South-eastern Marginal Mixed Farming Zone					
	Adaptation Action	**Interacting Sector**			
		Water	**Biodiversity**	**Agriculture**	**Other**
Agriculture	Change crop types			Possible reduction in production of economically or socially important crops.	
	Development of more resilient crops				
	Change sowing dates	Increase in water demand			
	Expand irrigation	Decreased water supply to other users Possible water saving techniques could be incorporated	Reduced water flow in the wetlands of the lower Tana		
Water	Building dams	Reduce downstream flooding Decreased water supply to other users.	Prevent species movement Loss of riverine species		Mitigation: reduce demand for fossil fuels if used for HEP
	Rainwater harvesting				
	Afforestation/ Reforestation	Reduced river flow in rainy seasons Reduced river flow in dry seasons	Habitat change Improve diversity	Possible loss of agricultural land Shade trees on farmland	Mitigation: carbon sequestration

Table 8-3

		Restore water quality			
Biodiversity	Expand protected areas			Possible loss of agricultural land	
	Maintain wildlife corridors				

Table 8-4: Pastoral zones: Adaptation actions and their interactions. Positive interactions are in black and negative interactions in red. Blank boxes indicate that no interactions were identified.

Pastoral Zones (South-eastern Pastoral Zone / Grasslands Pastoral Zone / North-eastern Pastoral Zone)					
	Adaptation Action	**Interacting Sector**			
		Water	**Biodiversity**	**Agriculture**	**Other**
Agriculture	Development of more resilient crops				
	Change sowing dates	Increase in water demand			
	Expand irrigation	Decreased water supply to other users Possible water saving techniques could be incorporated	Reduced water flow in the wetlands of the lower Tana		
Water	Floodplain restoration	Improve water quality	Improve biodiversity	Possible loss of agricultural land	Mitigation: carbon sequestration
	Wetland restoration	Improve water quality	Improve biodiversity	Possible loss of agricultural land	
	Rainwater harvesting and storage				
	Afforestation/Reforestation	Reduced river flow in rainy seasons Reduced river flow in dry seasons Restore water quality	Habitat change Improve diversity	Possible loss of agricultural land Shade trees on farmland	Mitigation: carbon sequestration

Table 7-4

Biodiversity	Expand protected areas			Possible loss of agricultural land	
	Maintain wildlife corridors				
	Better regulation in the protected areas				Mitigation: Could reduce emissions from deforestation

Table 8-5: Tana Riverine Zone: Adaptation actions and their interactions. Positive interactions are in black and negative interactions in red. Blank boxes indicate that no interactions were identified.

Tana Riverine Zone					
	Adaptation Action	**Interacting Sector**			
		Water	**Biodiversity**	**Agriculture**	**Other**
Water	Wetland restoration	Improve water quality	Improve biodiversity	Possible loss of agricultural land	
	Building dams				
Biodiversity	Expand protected areas			Possible loss of agricultural land	
	Develop new protected areas			Possible loss of agricultural land	
	Maintain wildlife corridors				

Table 8-6: Coastal zones: Adaptation actions and their interactions. Positive interactions are in black and negative interactions in red. Blank boxes indicate that no interactions were identified.

Coastal Zones (Coastal Medium Potential Farming Zone / Coastal Marginal Agricultural Mixed Farming Zone)					
	Adaptation Action	**Interacting sector**			
		Water	**Biodiversity**	**Agriculture**	**Other**
Water	Wetland restoration	Improve water quality	Improve biodiversity	Possible loss of agricultural land	
Biodiversity	Expand existing protected areas			Possible loss of agricultural land Possible loss of land for wind energy development	
	Develop new protected areas			Possible loss of agricultural land Possible loss of land for wind energy development	
	Maintain wildlife corridors				

8.2.1 No or low Risk Adaptation Options

It is important to consider low or no-risk (hereafter "low risk") options for each sector. These are options which provide benefits regardless of the uncertainties in the climate change projections (Hallegatte, 2009). One important adaptation measure identified to address climate change impacts on biodiversity that can be considered low risk is maintaining wildlife corridors and landscape connectivity. This is particularly important within the pastoral zone, where the greatest difference between the number of case study mammals and birds remaining was seen between the two dispersal scenarios. Berry *et al.* (2013) note that biodiversity adaptation measures are generally compatible with other adaptation strategies, except where the requirements of one species is in opposition to those of another species of conservation concern.

Similarly, rainwater harvesting and storage can be considered a low risk adaptation option. Another low risk option would be encouraging water saving techniques and behaviour in both the Tana River Basin and in Nairobi to reduce the demand for water (and water stress as a result). Promoting efficient water use is noted as a short-term adaptation action in Kenya's National Adaptation Plan (GoK, 2016). Finally, developing more resilient crop varieties can be seen as a low risk option. Developing resilient crop varieties has been seen as vital in adapting agriculture to climate change (Ceccarelli *et al.*, 2010). All of these low risk adaptation options are appropriate for the entire Tana River Basin.

8.2.2 Potential for Trade-offs within the Tana River Basin

Figure 8-3 summarises the main trade-offs between sectors and adaptation options for each livelihood zone within the Tana River Basin that have emerged from this study.

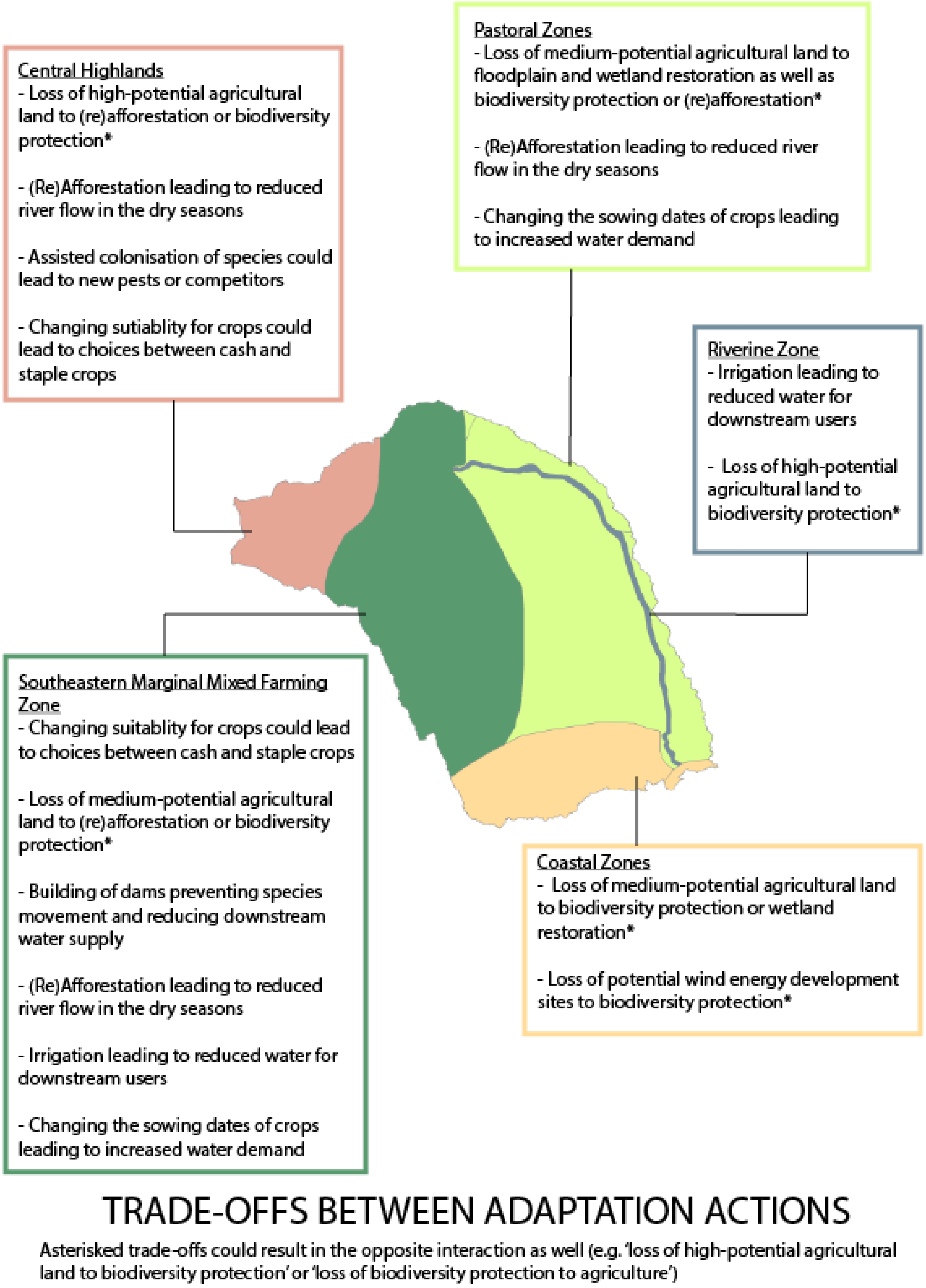

Figure 8-3: Potential trade-offs identified between potential adaptation options for the Tana River Basin which were identified in this study. Livelihood zones data source: Famine Early Warning Systems Network (FEWSNET, 2011).

8.2.2.1 The Central Highlands

Table 8-2 showed the main interactions between adaptation options for the Central Highlands. The rehabilitation of the water towers, which is highlighted in several GoK policies including the National Adaptation Plan, is likely to involve reforestation or afforestation. Afforestation can increase water demand in the Central Highlands. Changing land uses by increasing tree cover can result in changes in the water cycle through increases in evaporation and reductions in runoff (Trabucco *et al.*, 2008). Mwangi *et al.* (2016) showed that agroforestry in Kenya's Mara River Basin reduced overall water yield. The Tana is the only permanent river in this study area, so changes to the water in the highlands near its source will have implications for the whole basin. Nakaegawa and Wachana (2012) showed that water use trade-offs already occur in the upper Tana basin, which also affect the tribes relying on flood waters in the lower Tana. Reductions in river flow as a result of (re)afforestation are likely to be of particular importance in the dry seasons when water resources are extremely limited.

Afforestation, and possibly biodiversity protection, could also limit the land available for agriculture. Much of the land in the central highlands was classified as high potential agricultural land. Loss of potential agricultural land to these other land uses could lead to the intensification of agriculture elsewhere.

Additionally, depending on the tree species used for (re)afforestation, this adaptation measure could reduce habitat diversity and complexity. Similarly, biological diversity could be affected by assisted colonisation as a strategy for preserving biodiversity. Assisted colonisation can lead to new interactions between the introduced species and those already inhabiting the area. These interactions may be predator-prey relationships, competition for resources or related to the introduction of new pests and diseases.

In the Central Highlands, trade-offs may also occur between different crop types. Results suggest that the upper basin may become more suitable for staple crops like millet but this area is already dominated by economically-important cash crops (i.e. tea and coffee). In addition, these areas where crop yields may increase in the upper Tana are also the areas where the GCMs disagree most on whether rainfall will increase in the future.

8.2.2.2 South-eastern Marginal Mixed Farming Zone

Table 8-3 showed the main interactions for the mixed farming zone. Hydropower potential is already being exploited in the Upper Tana and development agendas aim to increase HEP in the basin. These additional dams are planned for the South-eastern Marginal Mixed Farming Zone. Vorosmarty *et al.* (2010) found that building dams to store and control water can have significant effects on the biodiversity around the dam site. Building dams could prevent the movement of species and lead to further habitat loss, which could contribute to projected biodiversity losses with climate change. Building additional dams will also reduce the water supply for downstream users.

Expanding irrigation within this zone could have a similar effect. This reduction in water supply is likely to have knock-on effects for the wetlands around the Tana Delta. The use of water for irrigation can compromise biodiversity protection (Berry *et al.*, 2013). Wetland habitats, which have a high biodiversity, are likely to be affected by water abstraction for irrigation upstream. In addition, if irrigation is not managed effectively, this could lead to increased soil erosion.

Earlier planting could lead to an increase in water demand within the zone. Similarly, as shown for the Central Highlands (Section 8.2.2.1), choices between crop types may be necessary.

The negative effects of (re)afforestation with regards to water resources and agriculture have already been discussed in Section 8.2.2.1 but are likely to be important within this zone as well.

By contrast, expanding protected areas within this zone was shown to have the potential to help preserve biodiversity. However, this is likely to lead to the loss of medium-potential agricultural land.

8.2.2.3 Pastoral Zones

Table 7-4 showed the main interactions for the pastoral zones. The loss of land with a high-medium potential for agriculture to other land uses is a key trade-off in the pastoral zones. Reductions to the land available for agriculture are associated with floodplain restoration and wetland restoration. Other interactions likely within this zone, such as those associated with expanding irrigation, afforestation and expanding PAs, have already been discussed in Sections 8.2.2.1 and 8.2.2.2.

8.2.2.4 Tana Riverine Zone

It is also possible that a hotspot of trade-offs over water and land use may occur along the mid-reaches of the main Tana River (Table 8-5). As seen above, many trade-offs within this zone are associated with the potential loss of agricultural land to other uses. This zone is projected to contain refugia with all levels of warming and so new PAs may be necessary to better protect biodiversity. However, with increased irrigated agriculture planned along the river, it may not be possible to fully protect wildlife in this area, which could lead to larger overall reductions in species richness.

Furthermore, as discussed in Section 7.2.2.2, expanding irrigation is likely to reduce the volume of water available for downstream users. Extracting water in the mid-reaches of the river may negatively affect water quantity and quality in the Tana Delta.

8.2.2.5 Coastal Medium Potential Farming Zone

As seen with the Tana Riverine Zone, within the coastal zone, trade-offs are likely between protecting biodiversity and economic development (Table 7-6). Areas that should be turned over to wildlife conservation to maximise biodiversity protection in a changing climate coincide with current plans for the development of the area, which include medium-potential agricultural land and wind energy development. Similarly, restoring wetlands could lead to the loss of agricultural land.

8.2.3 Potential for Synergies within the Tana River Basin

Figure 7-4 summarises the main synergies between sectors and adaptation options for each livelihood zone within the Tana River Basin that have emerged from this study. It is important to note that some adaptation measures that have been identified, such as afforestation, could lead to synergies as well as trade-offs, depending on the location and scale of the intervention as well as the type of trees chosen.

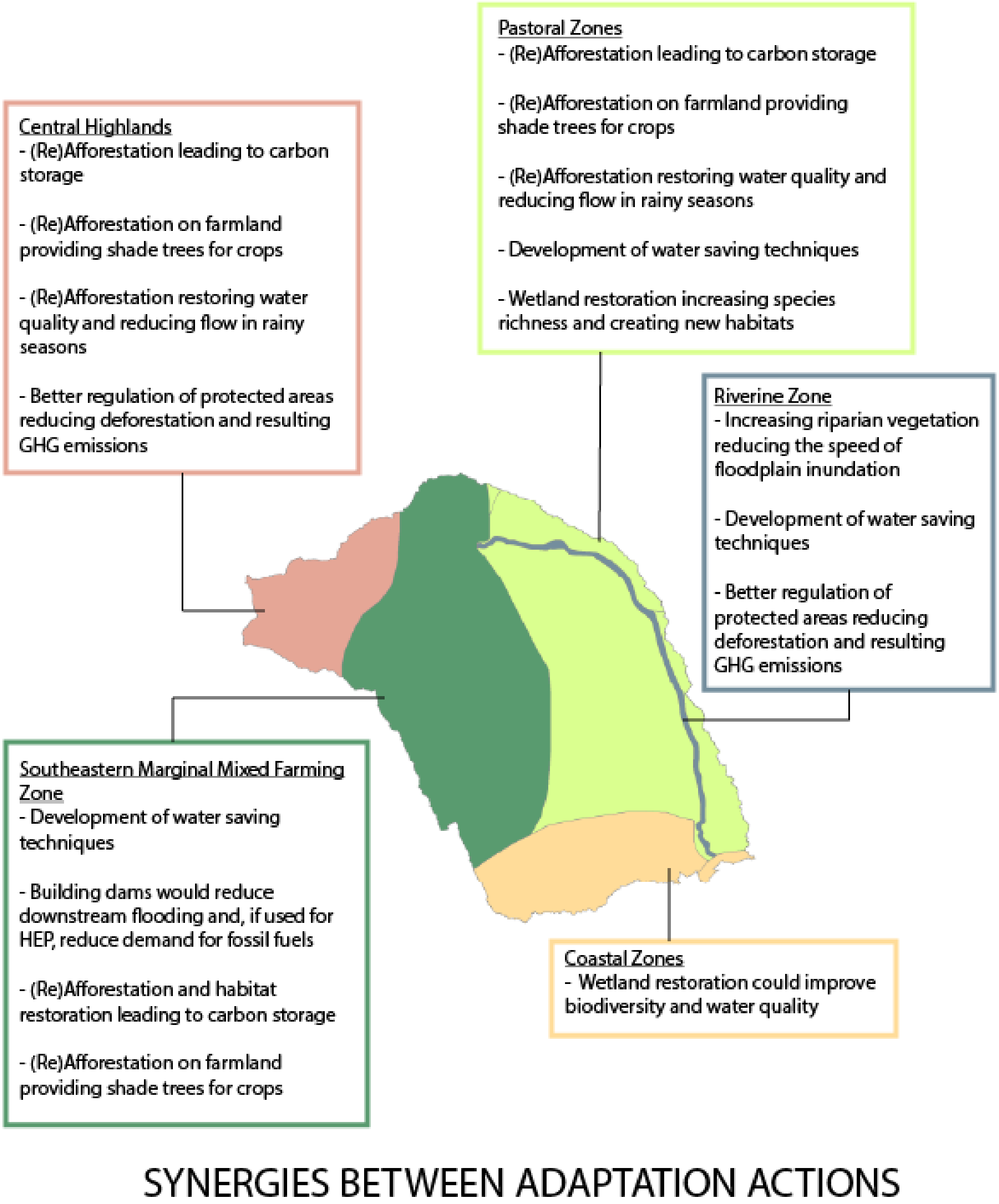

Figure 8-4: Potential synergies between adaptation options for the different livelihood zones of the Tana River Basin which were identified in this study. Livelihood zones data source: Famine Early Warning Systems Network (FEWSNET, 2011).

8.2.3.1 Central Highlands

Afforestation or restoration plans will improve water quality, reduce river flow in the rainy seasons and potentially alleviate flooding downstream. In addition, the resulting habitat change may improve the area for biodiversity. Tree planting is a popular soil management practice in eastern Kenya (Recha *et al.*, 2016). Afforestation could also involve planting shade trees on agricultural land, which will have benefits for the crops below. Furthermore, increasing tree cover has potential carbon sequestration benefits. Forests exhibit a high capacity for the provision of long-term carbon sequestration (MEA, 2005). Similarly, better regulation of the existing PAs in the Central Highlands, through reducing illegal deforestation also has the potential to reduce emissions and improve water storage.

8.2.3.2 South-eastern Marginal Mixed Farming Zone

A number of adaptation strategies were found to have potential for synergies in the South-eastern Marginal Mixed Farming Zone. The proposed dams all occur in this zone. Additional dams could reduce downstream flooding in the rainy seasons. If these dams are used for HEP, they may also reduce the demand for fossil fuels.

Expanding irrigation in this zone may allow for water saving techniques to be developed and incorporated into new and existing irrigation projects within the basin. Water-saving irrigation has the potential to lessen the negative impact of climate change on agriculture and increase water productivity (Belder *et al.*, 2005). Rosenzweig and Tubiello (2007) suggested that often mitigation and adaptation strategies in agriculture are synergistic, for instance increased irrigation enhancing carbon sequestration.

Synergies associated with (re)afforestation or habitat restoration are also important in this zone and are described above (Section 8.2.3.1).

8.2.3.3 Pastoral Zones

Protecting biodiversity in the pastoral zones may involve habitat restoration, which could have benefits for water resources. Wetland restoration, which is noted as important in the National Water Master Plan 2030, could have additional benefits, such as increased species richness and habitat creation for threatened species. Similarly, biodiversity protection projects that aim to enhance carbon-rich ecosystems like forests, will contribute to mitigation through carbon storage. The benefits of (re)afforestation were discussed in Section 8.2.3.1.

Additional irrigation within this zone, combined with limited water availability, may lead to the development of water saving irrigation techniques which can be employed more widely across the basin. This was also discussed in Section 8.2.3.2.

8.2.3.4 Tana Riverine Zone

Restoring riparian vegetation cover in the Tana Riverine Zone could have additional benefits for reducing the speed of floodplain inundation during floods.

The synergies associated with expanding irrigation were discussed in Section 8.2.2.2. Better regulation of the PAs in this zone may also reduce deforestation.

8.2.3.5 Coastal Zones

Wetland restoration has the potential to improve biodiversity and water quality within the coastal zones. Wetlands can also be effective for mitigating climate change through increases water infiltration and storage compared to other land uses (Mitch and Gosselink, 2000).

8.2.4 Trade-offs Vs. Synergies

This research found a greater number of cross-sectoral interactions (between the adaptation strategies identified here) can be considered negative and could result in trade-offs. Given the existing competition for water and land, some trade-offs are inevitable (Viguie and Hallegatte, 2012). The loss of agricultural land has frequently been identified as the result of pursuing many adaptation options, such as siting new PAs or (re)afforestation. The agriculture sector has the greatest number of potential trade-offs across the basin but important negative interactions were identified for water and biodiversity as well.

Reducing the trade-offs associated with limited land availability could be achieved through multi-functional land use. As discussed in Section 8.1.3, fruit trees may address afforestation goals as well as increasing agriculture. Furthermore, educating communities on the importance of other land uses, particularly biodiversity protection, may alleviate conflicts. Reducing natural resource based conflicts is highlighted as an important adaptation measure in Kenya’s National Adaptation Plan (GoK, 2016).

Positive interactions (synergies) were also identified for each livelihood zone of the Tana River Basin. The sector with the greatest number of synergies was water, where many adaptation measures were found to have benefits for water quantity and quality. In their literature review of cross-sectoral interactions between adaptation and mitigation measures in Europe, Berry *et al.* (2015) also found more potential synergies between water and biodiversity than between other sectors. Berry *et al.* (2013) stated that it is logical to promote strategies that have a high number of synergies. However, it is also important to consider other aspects of the options, such as flexibility and their potential to increase resilience within the system (Adger *et al.*, 2005; Hallegatte, 2009).

It is also important to avoid assuming that the number of trade-offs or synergies within a zone or sector represents their importance. Some trade-offs are likely to have greater effects on the Tana River Basin than others.

In their literature review for the CLIMSAVE project, Berry *et al.* (2015) found more examples of synergies between adaptation and mitigation measures across Europe than conflicts (or trade-offs). However, their analysis included more sectors (including coasts and urban areas) and considered a larger study area than this thesis.

8.2.5 Which adaptation actions are the most urgent?

Of the numerous adaptation actions identified within this study, some can be seen as more urgent than others. Encouraging water saving techniques and behaviour in both agriculture and among the wider population can be seen as an important adaptation strategy and is recognised within the National Adaptation Plan (GoK, 2016). This was identified as a low risk adaptation option in Section 8.2.1. Promoting efficient irrigation systems could contribute to this. Behavioural change and development of more water efficient technologies is likely to take a long time to achieve. Therefore, starting the process should be seen as a priority.

Improving the use of resilient crop and tree species can also be considered important. The National Adaptation Plan (GoK, 2016) does note the importance of improving knowledge of and access to climate-resilient tree species but this is considered a long-term (>6 years) action. By contrast, tree-planting is classed as a short-term action. Tree-planting may become maladaptive if the wrong species are used. Therefore, improving the use of climate-resilient species should be a priority, rather than a long-term action.

Furthermore, ensuring that PAs are able to protect a wide range of species in a changing climate is an important adaptation measure. This may involve creating new PAs or maintaining the connectivity between the existing PAs. Ensuring that the species have suitable PAs may reduce human-wildlife conflict as species begin to disperse. In addition, wildlife tourism is an important sector of the Kenyan economy. Other than the loss of land for other uses, most biodiversity adaptation strategies identified in this study have no trade-offs with other sectors or adaptation measures. Although the GoK does not include plans for adapting the PA network in their National Adaptation Plan, the Wildlife Corridors and Dispersal

Areas Report (Ojwang' *et al.*, 2017) recognises the importance of allowing species to move across the landscape and maintaining PAs.

Other adaptation actions that were identified may become necessary further into the future but cannot be considered urgent now. An example of this would be assisted colonisation to ensure biodiversity protection. Assisted colonisation cannot be considered a current priority, but if reductions in species richness and localised extinctions are realised, this method of adaptation may become more important.

The construction of new dams, although favoured by the GoK, has not been identified as a priority in this study. Numerous trade-offs associated with additional dams were identified in Section 8.2.2. The substantial seasonal variation in water availability under current climate conditions has already resulted in siltation in the existing dams during dry seasons and dams overflowing in the rainy seasons (FEWSNET, 2018). Instead of focusing on dam construction, which will require significant financial resources, improving other water storage means should be considered first. In addition, the uncertainty over projected increases in rainfall compared to the current drying trend should also be considered. Therefore, dam construction could instead be considered a long-term adaptation action for the Tana River Basin.

8.3 Can the Tana River Basin be considered a hotspot of projected climate change impacts and risks?

It is interesting to consider whether the Tana River Basin as a whole could be considered a hotspot of projected climate change impacts when compared to other regions. There are various components to this: vulnerability, magnitude and confidence in the projections. Vulnerability to climate change is affected by a great many factors. The Tana River Basin could be considered a hotspot of projected climate change impacts because of the changes analysed here and other underlying vulnerabilities. These results have shown that climate change has the potential to severely alter the biodiversity and agricultural productivity of the basin. In addition, increases in rainfall in the wet seasons could increase the risk of flooding, while reductions in precipitation in the dry season could exacerbate droughts.

In addition, the population of the mid to lower basin is generally very poor (KBNS, 2018). Many African populations can be considered more vulnerable to the effects of climate change than the peoples of developed countries as their capacity to adapt is lower. In addition, there is already known to be poor regulation in the area, with many policies proposed by the central government not being fully implemented at the district level. Although there is evidence of rural Kenyans adapting to climate variability, the changes with climate change are likely to be more severe. Burke *et al.* (2009) argued that the majority of farmers in Africa will be faced with conditions beyond their personal experience by the 2050s. Furthermore, as water from the Tana River Basin provides most of the domestic supply to Nairobi, the effects of changes within the basin as a result of climate change will be felt outside of the basin.

The Tana River Basin has not been identified as a hotspot of projected climate change impacts and risks by any previous studies examining hotspots or cross-sectoral impacts of climate change. Diffenbaugh and Giorgi (2012) conducted a global scale study of changes to climatic variables using the CMIP5 models, but East Africa was not identified as a global climate change hotspot. It is likely that this is due to the uncertainty within the projections for this region, which has already been highlighted in Section 1. By contrast, Piontek *et al.* (2014) conducted a multisectoral study which identified the Ethiopian highlands as a hotspot for many of same reasons the Tana River Basin has been considered so here. However, as well as crop changes and biodiversity, malaria risk was included as a metric for human health. This makes Piontek *et al.*'s investigation different from this study. It is possible that the risk to human health is lower in the Tana River Basin, due to lower population densities, so the area would not appear a hotspot in Piontek *et al*'s study.

At the continental scale, Muller *et al.* (2014) determined hotspots of climate change risks in Africa based on exposure to impacts (i.e. total surface freshwater probability, flooding probability, occurrence of dry periods, irrigation water requirements, changes to crop yields and ecosystem productivity), population density and high poverty rates. The severity measure developed in Muller's study did not identify the Tana River Basin, or Kenya as a whole, as a particular hotspot of risks and impacts. This is partially due to the lower probability of dry periods and increase in total surface freshwater availability within Kenya shown in their modelling results compared to other African countries. However, the Tana River Basin has recently been the focus of a large project led by the IUCN which focused on river basin development (in which Baker *et al.* (2015) provided a baseline study and Sood *et al.* (2017) projected changes to hydrological variables with climate change), as discussed in Chapter 2, Section 7, which shows its importance. Results from Sood *et al.* (2017) were compared to the hydrological projections from this study in Chapter 5, Section 5.4.

8.4 Policy Implications

International, national and local policies are one way to reduce and enable the resolution of trade-offs as well as maximising the potential synergies. This section will discuss the implications of the current policies in light of the results presented here and then other policy implications of the main findings.

8.4.1 Implications of the management plans considered in this research

First, it is important to consider the implications of the policy documents and management plans which have been analysed for this research. Generally, there is limited direct consideration of climate change in these policies, in particular in the 2017 National Spatial Plan. It is possible that the planning process took previous projections into account and that proposed increases in irrigated agriculture in the upper Tana are recommended because of possible higher future rainfall but this is not stated in the report. Similarly, in terms of biodiversity protections, wildlife corridors were mapped under existing conditions for the Report on Wildlife Corridors and Dispersal Areas (Ojwang' *et al.*, 2017). This did not account for range shifts with climate change, which have clearly been shown to be significant. As discussed in the Literature Review, the JICA conducted a study for the development of the National Water Master Plan, which only considered a narrow range of projections. Even if these projections were used to inform the National Spatial Plan and other recent policy documents, the uncertainty cannot be fully addressed. Without including the effects of climate change, these plans will likely lead to increased pressure on land, particularly in the north of the basin around the Central Highlands, and could lead to inappropriate land uses.

The results of this thesis show that climate change could severely affect the Tana River Basin. Therefore, a key recommendation would be that the GoK start actively considering climate change in policies now rather than planning to do so in the future. New policies are still being produced without the effects of climate change directly considered in them (e.g. the National Spatial Plan which was launched in late 2017). The individual flagship projects for the Tana River Basin set out in the Vision 2030, such as the Galana-Kulalu Food Security Project (Baker *et al.*, 2015), should be re-evaluated with the effects of climate change borne in mind. If this re-evaluation is undertaken, it is possible that there is still time to alter plans to more adequately account for climate change and reduce the potential trade-offs that could occur within the Tana River Basin.

8.4.2 Implications of these results for policy makers

The results of this thesis could have important implications for management and policy within the Tana River Basin. Tourism (predominantly wildlife tourism) and agriculture were identified as two of the most important sectors for spurring development and economic growth in the Vision 2030 (Ndung'u *et al.*, 2011). The importance of sustainable use of water is acknowledged throughout the Vision, both for the environment and for water and sanitation for human uses. Therefore, understanding potential changes to these sectors is vital for effective policy formation.

As shown in Section 7.1, improvements to water efficiency and demand management would contribute to the more sustainable use of water resources across the basin. Even with increases in water availability projected, the demand is likely to be greater than the supply. With continuing population growth, HEP and agricultural water uses, there will be a growing need to balance the water use between the different users in the basin. Encouraging water saving behaviour and education is an important method for preparing and adapting to a changing climate.

There are likely to be differences in the ability to adapt to the impacts of climate change across the basin, both as a result of the impacts themselves and the vulnerability of the local population. A recent report by the Kenya Bureau of National Statistics (KBNS, 2018) showed that the Tana River Basin contains some of the richest and poorest counties in Kenya. This was measured by the number of people living in poverty. Nyeri and Meru are the richest counties within the basin (second and third in the country as a whole). By contrast, Garissa was the fifth poorest in the country. Tana River is also among the ten poorest counties in the country. Targeted policies for different areas of the basin may be more beneficial than generic policies. The importance of this approach to climate change adaptation in East Africa is supported by van Wesenbeeck *et al.* (2016). These targeted policies must ensure that all users have fair access to resources. McCord *et al.* (2018) argued that smallholder access to irrigation water is crucial for this adaptation strategy to be successfully adopted.

Additional PAs or improvements to the corridors connecting existing PAs may be needed to preserve a greater number of species. New PAs could increase the connectivity between existing areas or act as climate refugia themselves. Possible new PAs, which could account for a higher number of species, were proposed in Chapter 5. Similarly, important 'dispersal' areas for birds and mammals were identified in the central basin. Alternatively, the conservation planning framework (Carvalho *et al.*, 2011) could be used to identify other suitable sites.

It is possible that trade-offs could be reduced through multi-functional land use (DeFries and Rosenzweig, 2010). To be effective, this would need to consider multiple stakeholders as choices of land use might differ between interested parties in accordance with national agenda, local needs and individual preference. However, it is important to note that scientific knowledge is just one factor in policy-making (Marshall *et al.*, 2017). In their study on conservation in policy, Rose *et al.* (2018) concluded that public support is essential for long-term, pro-environmental policy and support. Furthermore, the spatial variations in impacts and adaptation options across the basin demonstrate the importance of effective governance at the district level.

8.4.3 Barriers

There exists a number of barriers to the effective development and implementation of adaptation and mitigation schemes as well as strategies for reducing trade-offs within the Tana River Basin. It has been noted that existing adaptation in Africa tends to be in response to short-term motivations (Niang *et al.*, 2014). This type of decision-making may lead to policies that benefit the country in the shorter term but lead to further problems in the longer term. Conway and Schipper (2011) found that the need for governing bodies in Ethiopia to move away from short term thinking in order to focus on a longer-term perspective of vulnerability reduction would be a fundamental shift in thinking.

These results demonstrate the need for adaptation and building resilience in the face of uncertainty. Relatively little is known about how policy changes, leading to decreases in GHGs, may mitigate against the impacts on biodiversity (Price *et al.*, 2013). Human development is always the priority for policymakers and therefore human interests must be considered. Chapman *et al.* (2006) used primate diversity in Africa to show that the future of successful conservation of these species will be dependent upon political and economic stability across the continent. However, there are multiple benefits to humans of protecting biodiversity, including the health benefits – particularly mental health benefits – of interactions with nature and the ecosystem services that natural environments provide.

The success of policies also depends on the implementation efficiency at the local level (La Jeunesse *et al.*, 2016). Gainer *et al.* (2015) showed that in the past, as governmental personnel changed in Kenya, local policies and projects have been abandoned. Similarly, ministries often have other existing priorities. Biesbroek *et al.* (2010) argued that, for adaptation to be successful, public and private actors must collaborate across all levels of governance. Bottom-up approaches to decision-making have been found to highlight cross-sectoral interactions (Urwin and Jordan, 2008). Top-down approaches can often lead to antagonisms. Beveridge *et al.* (2018) also recognised the importance of locally-relevant strategies for successful adaptation within the agricultural sector.

8.5 Strengths of this research

There are several particular strengths of this research which should be highlighted. Firstly, this research provides a quantitative assessment of hydrological change, which is required for management of water resources. This research has analysed a large river basin in a data-poor environment, which has only one main gauging station. This also shows the value of the hydrological model, as WaterWorld uses spatial, remotely sensed input datasets and does not rely on local data availability.

Furthermore, the benefits and challenges of data integration between different models and sectors were highlighted in this thesis. The challenges of cross-sectoral work was also highlighted by van Wesenbeeck *et al.* (2016), who determined the vulnerability of the local population based on a number of different indicators in areas that are already known to be vulnerable to climate change in both East and West Africa. They found that a trade-off between the number of variables included in the analysis and the coverage of the most important variable was necessary for useful results.

This research shows the need for cross-cutting adaptation and has highlighted gaps in the current development and management plans. For instance, examining individual species as well as taxa level changes has allowed for the identification of particular species that will not be protected by the current PA network and located the best sites for new PAs to protect future habitat space and represent a larger number of species.

This research also demonstrates the need for efficient use of freshwater resources in this area, particularly in the lower Tana, where water balances are likely to remain negative in the future (i.e. AET is greater than rainfall). Results of this thesis also further highlighted the large disagreement between the climate projections for this region of Africa, resulting in uncertainty in the impact model projections.

8.6 Uncertainties and Limitations

As well as the strengths of this research, some important sources of uncertainty and limitations must be considered. The limitations specific to each method have been discussed in the relevant chapter and some general limitations were noted in Chapter 3. The limitations with the WaterWorld model were discussed in Chapter 5. In Chapter 6, the limitations associated with the Wallace Initiative database (absent species, sub-grid scale refugia or areas of concern) were discussed. Additionally, the effects of factors that could not be included in the simulations, such as pests, pathogens, extreme events, the effects of increasing CO_2 concentrations and interactions between species, were discussed in relation to the investigation of species distribution changes in Chapter 6. Similarly, pests and diseases and extreme climatic events were considered as limitations with the analysis of crop yield and suitability changes in Chapter 7. Another limitation discussed in Chapter 7 was the relatively small number of GCMs employed in the ISI-MIP project compared to the numbers considered for the other sectors in previous chapters.

As limitations associated with extreme events (e.g. floods, droughts or heatwaves) and inter-annual variability are common throughout the chapters (as discussed in Chapter 3), it is important to consider their implications on the results. Extreme events are projected to increase in intensity, duration and frequency (IPCC, 2012; NAS, 2016). If extreme events were included, it is likely that the impacts of climate change on the sectors would be more negative. For biodiversity, extreme events are likely to lead to increased risk of extirpation (localised extinction). Extreme events can impinge on species directly, for instance through thermal intolerance, or indirectly by affecting their food or habitats (McDermott Long *et al.*, 2017).

Including extreme events could lead to results that showed many species are actually more sensitive to changes in climate than previously thought. Similarly, extreme events could affect all stages of agricultural production (as explained in the Literature Review). Crop damage from flooding is already a problem in the Tana River Basin (ACAPS, 2018). It is likely that these results are an under-estimation of the impacts of climate change because they do not consider extreme events.

In addition to these, there are some overall limitations that must be stated. First, it is important to consider the time horizon. The 2050s was the main focus of this study, although the 2070s (for hydrology) or 2080s (for biodiversity) were considered in some cases. Differences in radiative forcing are more substantial after 2050 (Zhu and Ringler 2012; Andersson *et al.* 2011). If 2070s had been considered for all sectors, the range of results may have been more substantial. Challinor *et al.* (2014) found that yield losses are greater in magnitude for the second half of the century than for the first. However, the choice of the 2050s for the agriculture analysis in this research was justified by the focus on this time horizon in Kenya's development plans.

Furthermore, there are numerous limitations of the climate data and models used throughout. The uncertainties associated with GCM projections were discussed in Chapter 3. Climate changes may have been over or underestimated as a result of the models. More precise projections of precipitation would be extremely useful and could reduce the uncertainty in the results. In addition, differences in the number of GCMs used to drive the impact models in each sector are an important limitation. In WaterWorld, between 12 and 19 GCMs are available depending on the RCP, whereas for the ISI-MIP project only 5 GCMs were considered. The results from the Wallace Initiative show the agreement between 21 GCMs. Improvements in the results could be achieved through weighting of the GCMs. However, studies have shown that policymakers want information about the uncertainty and associated risks, so an important goal of modelling is to provide this type of material (Pappenberger and Beven, 2006). It is extremely likely that our knowledge of social and ecological systems will never be complete, because these systems are so complex (Berkes, 2007). Instead, ways of dealing with and living with uncertainty must be found.

It has already been shown in Chapter 4 that the climate model projections and observations are not consistent in the direction of change in precipitation for Kenya. This could mean that the GCMs are missing important effects, or it could be that the drying trend seen in the observations is a short-term anomaly. It is not possible to determine which of these is correct. Therefore, a major caveat to this research is that, if the GCMs are failing to capture future drying trends, then the results and implications could be significantly affected. If the drying trend seen in the observations continues, the impacts of climate change could be very different from those presented here. Reductions in water balance and increases in water stress would be very likely with drier future conditions. This reduction in available water resources would also affect biodiversity, livestock and crops. Reductions in the water available for agriculture could lead to a reduction in yield, as shown with many of the 'no irrigation' scenarios examined in Chapter 7. In many ways, a drier future climate would be more problematic for the Tana River Basin and would lead to more negative impacts and potentially greater trade-offs.

Finally, other sectors, such as forestry, urban development, coasts and even risks to health, should also be considered to fully understand cross-sectoral trade-offs and synergies. Impacts on these sectors, as well as sectoral adaptation and mitigation options, may also affect the sectors considered here. There is already a significant volume of work on the possible impacts of climate change on human health; for instance, the changes in malaria risk (Patz and Olson, 2006). However, including the implications of this were outside the scope of this research project. Similarly, changes to water resources will have implications for hydropower energy generation in Kenya. As this study did not specifically address streamflow, it is difficult to provide any detailed conclusions on how HEP dams on the Tana River network will be affected.

There are additional adaptation strategies that have not been identified in this thesis which may be important to Kenya's efforts to respond to climate change. Some additional adaptation strategies which were not identified and recommended through the results of this study were noted in Section 8.1.7. Conducting a meta-analysis of the literature on adaptation strategies in Kenya may have provided a broader range of adaptation options for the three sectors but this was not the main focus of this study. Objective I aimed to project the impacts of climate change on the sectors. Modelling the projected impacts on these sectors allowed for a comparison with the large-scale management plans, which may not have been possible using other methods.

Consequently, conclusions drawn in this study should be interpreted by taking into account the uncertainties in and limitations with the results.

8.7 Areas for further study

To further address climate change related risks to the Tana River Basin, a number of pathways for future research have been identified. Firstly, employing additional local datasets, for example more detailed land use maps, could improve the assessment. Many authors have noted that different distributions of land uses can have different effects on water availability (Bruijnzeel, 2004; Legesse *et al.*, 2003; Memarian *et al.*, 2014). More detailed information on land use changes would aid land use planning and provide a better understanding of the potential risks or benefits of land use change in a changing climate.

Data scarcity is a common problem with research in Africa. However, authorities are acknowledging the problem and encouraging monitoring of these changes (Alila and Atieno, 2006). The WaterWorld model has the capacity to incorporate better resolution datasets provided by the user. As these datasets become more readily available for Kenya, they can be added to model analyses to gain a better understanding of local hydrological and land use change.

Considering the effects of possible changes to groundwater resources as well as surface water would also provide a greater understanding of the impacts of climate change. The lack of consideration of groundwater flow in the WaterWorld model was noted in Chapter 4 as an important limitation with the model. Adhikari *et al.* (2015) argue that the feasibility of groundwater irrigation systems is limited by the lack of studies evaluating the impacts of climate change on groundwater. It is likely that groundwater resources will be less altered by near-term climate change than surface waters so they may provide a valuable alternative to relying on surface waters (Bonsor *et al.*, 2010). Therefore, fully understanding changes to groundwater would be an important aim of future research.

In addition, although the choice of the WaterWorld hydrological model was clearly justified in Chapter 4 because of data constraints, employing a range of hydrological models, similar to the crop models from the ISI-MIP project, could provide a greater range of results and possibly improve the robustness of conclusions. Moreover, as discussed in the limitations (Section 7.6), this research has only considered changes to the mean climate but extreme events are also very likely to affect the region. Employing different hydrological models, which can operate at a daily time-step, would allow future research to better understand extreme events and their impacts.

The analysis of both biodiversity and agricultural change could be extended by considering a greater number of individual species. For instance, including pollinators and pests would provide a clear link between biodiversity and agriculture. This was noted as a limitation in both Chapters 5 and 6. Jaramillo *et al.* (2011) noted the importance of the coffee berry borer on future coffee production, showing that pests could severely impact crop production in Kenya. Additionally, analysing a greater number of reptiles and amphibians would strengthen the research. To further this, the interactions between different species, for example across the trophic levels, would be beneficial.

Furthermore, changes to water quality could be considered as well as changes to water quantity. Alterations to water quality are considered alongside changes to water quantity in the National Water Master Plan, so are known to be important in Kenya. Kithiia (2011) notes that water resources in rural Kenya are also under pressure from agricultural chemicals and industrial waste. Increased agricultural activity will also degrade water quality due to the leaching of chemicals and nutrients into the river system and groundwater sources (Foley *et al.*, 2005).

Finally, another area of further study would be to develop a method of quantifying cross-sectorial impacts. Other ‘hotspots’ research has attempted to do this (e.g. Muller *et al.*, 2014) with varying levels of success. Muller *et al.* (2014) found that in order to quantitatively identify hotspots, the number of metrics included in the index needed to be more limited. Despite these difficulties, quantifying the multi-sectoral climate change impacts across the basin may make a future analysis more robust and hotspots more straightforward to identify, which would be particularly beneficial for decision makers. Similarly, considering other sectors such as energy production or human health could prove a useful topic of future research because of their interactions with the sectors already considered. The effect of interactions with other sectors was noted in the limitations in Section 7.6.

Chapter 9 Conclusions and Future Research Recommendations

9.1 Revisiting research aim and objectives

This research aims to project the impacts of climate change upon the Tana River Basin for the 2050s in order to inform national climate change adaptation plans. This involved modelling the effects of climate change on the water, biodiversity and agricultural sectors and examining the interactions between the sectors and possible adaptation responses to climate change.

Within this, specific objectives are to:

(i) establish the range of projected climate change impacts on (a) water, (b) agriculture and (c) biodiversity conservation in the Tana River Basin across climate models and emissions pathways for the 2050s (2041-2060),

(ii) to examine the extent to which climate change adaptation is considered in existing policies,

(iii) to identify hotspots of trade-offs or synergies between the projected impacts of climate change in the three sectors (water, biodiversity and agriculture), the possible adaptation measures appropriate for each sector and existing development plans.

(iv) to investigate the uncertainties in projected climate change impacts that arise from the different GCMs and RCPs in order to inform robust policy and adaptation plans.

The results focused on the medium time horizon of the 2050s. Results were examined at the administrative level and compared to the protected area network and livelihood zones within the Tana River Basin where appropriate.

9.2 Overview of the Main Findings

To address Objective ia, the WaterWorld model was used to simulate hydrological change within the Tana River Basin. Projections of basin-average mean temperature change range from 1.3 for RCP2.6 to 2.1°C for RCP8.5 in the 2050s using the multi-model mean scenarios, whilst precipitation changes range from 12 to 16% increases for the same scenarios. Seasonal changes are expected, with rainy seasons experiencing higher rainfall and the dry season projected to see reductions in rainfall. Increases in water balance occur as a result of rises in precipitation. However, these projected increases in water supply are likely to be outweighed by increases in water demand from a growing population and economy.

To address Objective ib, projections extracted from the ISI-MIP FT and Wallace Initiative databases were used to examine changes to crop yield and suitability. Total yields of both sugarcane and millet are projected to increase in the future, whereas maize and wheat are likely to be negatively affected by the changes in climate. Other species that may prefer the future conditions include mango and pineapple. In addition, changes to the suitability of agroforestry and afforestation species was analysed.

In Chapter 6, the effects of climate change on the terrestrial biodiversity of the Tana River Basin were examined to address Objective ic. Increasing risks of biodiversity loss were seen with higher temperatures. Refugia for plants and animals are projected in the Central Highlands of the Upper Tana and around the coast in the Tana Delta. Some PAs are projected to overlap with these climate refugia. However, results showed that, at both the taxa level and for the case study species, the current network of protected areas could prove insufficient for conserving biodiversity both under current conditions and in a changing climate. When dispersal is included, the basin remains climatically suitable for a greater number of species. Facilitating movement will be extremely important for conserving biodiversity.

Overall, to address Objective i, this thesis has examined changes to the water resources, biodiversity and agriculture of the Tana River Basin and found that in all cases, the higher emissions scenarios lead to greater changes, demonstrating the importance of limiting warming through mitigation. Adaptation is also an urgent policy issue and will be necessary in order to avoid some of the negative effects of climate change in the study area.

Objective ii aimed to examine the extent to which climate change was considered in existing policies. The existing policies were discussed in the Literature Review in Chapter 2. Some existing policies, such as the National Spatial Plan and the National Adaptation Plan, were used to compare to the results of this thesis. Chapter 7 presented results from the WaterWorld model which combined the effects of climate change with projected land use changes. The influence of climate change on water balance was found be stronger than the influence of projected land use change, demonstrating the importance of considering climate change within land use and management policies.

Chapter 7 considered the potential adaptation measures appropriate for each sector considered in the previous chapters, before examining the potential for synergies and trade-offs between sectors and measures to address Objective iii. All sectors examined here have the capacity for adaptation, but even with adaptation, residual risks remain. The agricultural sector could adapt through changes to crop choices and water management. Adaptation options for the water sector include improving water storage, improving water use through technological development and efficient irrigation systems. Many of these adaptation options have indirect impacts on biodiversity. More specific biodiversity adaptation options are maintaining and improving connectivity between protected areas, enlarging some protected areas and possibly even assisted migration of species between protected areas. The negative interactions resulting in trade-offs were mainly concerned with water quantity and competing land uses. Many synergies relate to biodiversity and water. These options also have synergies with mitigation although it should be noted that mitigation was not the main focus of this study.

Some adaptation actions have been identified as more urgent than others. Urgent adaptation measures include encouraging water saving techniques and behaviour in both agriculture and among the wider population, improving the use of resilient crop and tree species and ensuring that PAs are able to protect a wide range of species in a changing climate. In general, these are in line with adaptation actions outlined by the GoK in their National Adaptation Plan. The remaining adaptation actions, such as assisted colonisation or dam construction) could be considered longer-term options. This advice, particularly in relation to dam construction, does not correspond with current GoK policies.

However, there is still a substantial amount of uncertainty in the projections, particularly of changes to rainfall within the basin. A range of models and climate change scenarios were used here to assess uncertainty and address Objective iv. However, there is a mismatch between the model projections (wetter conditions) and the recent observations (drying), which forms a major caveat to this research. Choosing effective adaptation and mitigation strategies in the face of ongoing uncertainty will be a significant challenge for managers and decision makers. The benefits of both adaptation and mitigation have been shown, particularly in relation to biodiversity protection. These might be able to reduce and, in the case of adaptation, compensate for some of the cross-sectoral impacts and demands of the different sectors. Decision makers need to think further into the future in order to ensure short term gains do not come with longer term losses. The conclusions drawn in this study should be interpreted by taking into account the uncertainties in and limitations with the results.

9.3 Policy Implications

This thesis contributes to the advancement of understanding of the impacts of climate change on the Tana River Basin and has provided some important conclusions which are relevant to policymakers in Kenya.

First, it is paramount that the GoK start considering climate change in the policies now rather than planning to do so in the future. Existing policies and individual flagship projects from the Vision 2030 should be re-evaluated with the effects of climate change borne in mind. Results have shown that substantial changes are likely to occur by the 2050s, showing the importance of timely action on climate change. Climate change cannot be treated as a stand-alone policy issue as it affects all sectors.

Some trade-offs between the sectors are inevitable. For instance, as increases in water demand are likely to outweigh increases in water supply, it is possible that decision makers may need to decide on priorities for water resource use when there is not enough water to meet all of the demands. In addition, the loss of land with a high agricultural potential to other land uses is likely. Reducing these trade-offs could be achieved through multi-functional land uses, encouraging water saving behaviour and by considering a range of stakeholders in decision making.

To better protect the biodiversity of the Tana River Basin, additional protected areas may be necessary. Designating new protected areas and improving the connectivity between existing PAs will go some way to supporting biodiversity conservation, which is likely to have implications for tourism.

Spatial variations in the projected impacts across the basin demonstrate the importance of effective governance at the district level. Similarly, removing barriers to adaptation through bottom-up approaches and involving communities in the decision making processes to ensure that the measures are locally appropriate should be a key policy concern.

9.4 Recommendations for Future Research in the Tana River Basin

For future research, four main points are suggested for consideration. First, incorporating new datasets into modelling studies as they become available in order to improve projections and reduce uncertainty. These additional datasets may facilitate the use of alternative hydrological models. Improvements to the biodiversity analysis could involve examining additional species as well as the interactions between the species. In addition, examining changes to climate variability and extreme events is an important topic for further research. Extreme climatic events will impact all sectors. It is likely that the results of this thesis are an under-estimation of the impacts of climate change because the effects of extreme events were not considered. Improvements to the cross-sectoral analysis, such as including other sectors or developing a method of quantifying cross-sectorial impacts, are also recommended for further research.

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Appendix I: Protected Areas within the Tana River Basin

Table AI-1: Protected areas within the Tana River Basin, sorted by area in sq km. (World Database of Protected Areas (2016)). Those highlighted in green have been included in the GIS analysis.

NAME	DESIGNATION	Area (km^2)
Tsavo East	National Park	11747
Mount Kenya National Park/Natural Forest	World Heritage Site	2023
Mount Kenya	Forest Reserve	2010
South Kitui	National Reserve	1833
Kora	National Park	1788
Rahole	National Reserve	1270
Ndera Community Conservancy	Community Nature Reserve	1155
Meru	National Park	870
Hanshak-Nyongoro Community Conservancy	Community Nature Reserve	792
Aberdare	National Park	766
North Kitui	National Reserve	745
Ishaqbini Hirola Community Conservancy	Community Nature Reserve	732
Bisanadi	National Reserve	606
Arawale	National Reserve	533
Lower Tana Delta Conservation Trust	Community Nature Reserve	512
Kikuyu Escarpment	Forest Reserve	376
Solio Ranch and Rhino Sanctuary	Private Ranch	200
Tana River Primate	National Reserve	169
Imenti or Upper Imenti	Forest Reserve	122
Mwea	National Reserve	68
Nyambeni	Forest Reserve	55
Ngaia	Forest Reserve	43
Witu	Forest Reserve	40
Kijege	Forest Reserve	33
Nuu	Forest Reserve	25
Makongo-kitui	Forest Reserve	24
Njuguni	Forest Reserve	20
Mutito	Forest Reserve	20
Kiagu	Forest Reserve	14
Mutejwa	Forest Reserve	13
Nyeri	Forest Reserve	12
Kikingo	Forest Reserve	12
Ngamba	Forest Reserve	11

Kierera	Forest Reserve	8
Thuuri	Forest Reserve	7
Kieiga	Forest Reserve	6
Thunguru Hill	Forest Reserve	6
Mutharanga	Forest Reserve	3
Lusoi	Forest Reserve	3
Munguni	Forest Reserve	2
Mataa	Forest Reserve	1

Appendix II: WaterWorld Model Documentation

The WaterWorld documentation is adapted from the Mulligan (2013b) supplementary information.

AGUAANDES/WATERWORLD VERSION 2 MODULES

Version 2 adds an energy balance based snow and ice module, some changes to the way evapotranspiration is handled and a module for the spatial distribution of water quality. As well as the climate and land use change scenarios and policy options available for application in version 1, version 2 also incorporates modules for understanding the impact of land and water management interventions including bench terraces, fanya juu/bari terracing, check dams and existing or new reservoir dams.

MODULE: Soil Erosion, deposition and transportation

Full wash erosion, transportation and sedimentation model

Erosion according to Thornes (1990), E=kQmSne-0.07Vc

Transport capacity (Tc) according to stream power (Q, slope).

Sediment transport (S)=min (sediment from upstream+local erosion, P)

Sediment deposition where S>P

MODULE: Snow and ice

Snow and ice model

Initial monthly snow cover according to MODIS

New snow is precipitation where T<<0

Full energy balance for snow accumulation and melting (after Walter *et al.* 2005)

MODULE: Water quality

Water quality (human footprint on water)

Calculates the % of water at a point which fell as rain on point and non-point potential sources of contamination upstream

MODULE: Land and water management

Land uses - as well as land use being defined by the cover of Tree, Herb and Bare functional types, land use can also be defined by the land use type which can be one of Pasture, Cropland, Natural, Protected, Mining, Roads, Urban, Oil & Gas. These types affect the water quality indices. The initial values for these covers are set according to available input maps but the covers can be changed with the land cover and change policy options.

Land use intensities - each land use has an associated intensity of use. This intensity is set to 1.0 by default for all land uses. The intensity value can be changed in order to reduce intensity (for example eco-efficient agricultural practices) or increase intensity (particularly destructive mining techniques).

AGUAANDES/WATERWORLD VERSION 1 MODULES

Version 1 of AguAAndes/Waterworld is a sophisticated model of spatial water balance which has been developed for data poor and spatially complex and heterogeneous environments. The model includes modules for distribution of rainfall through interaction with wind, occult precipitation through fog inputs, solar radiation receipt, potential and actual evapotranspiration on the basis of climate and vegetation cover, water balance and its cumulation downstream as runoff. There is also a simple model for soil erosion. The model requires some 140 inputs maps (all of which are provided with the system, globally) and calculates monthly and annual hydrological variable including water balance, runoff and soil erosion for a baseline representing year 2000 land cover and mean 1950-2000 climate. Users can run scenarios for climate change and land use change and examine the impact of these on hydrological ecosystem services including water quality and seasonality. Given the lack of global data on groundwater resources AguAAndes/Waterworld does not simulate subsurface hydrological processes associated with flows in soil and groundwater.

MODULE: hydrology

SUBMODULE: Atmosphere

Surface area

True surface areas (as opposed to planimetric areas) are calculated with the triangle method (Jenness, 2004). These are important for the accurate representation of surface area in montane environments. True surface areas can be 1.3 times the planimetric surface area for very steep rugged slopes.

Vegetation

Tree, herb and bare percentages from MODIS VCF are converted to fractions

Timesteps

The model iterates between four diurnal and 12 mensual timesteps (4 in each month) for a total of 48 timesteps for a complete run.

Input climate data

Key assumption: Winds bend around topography, taking the path of least resistance. It is sufficient to model these changes in direction without accounting for concentration (funnelling effects).

Wind directions are read and converted to the appropriate topographically affected wind direction by reading the appropriate wind direction file. Based on this wind direction, the appropriate TOPEX value is read from the topex files. Note that the wind direction file BLWind mis the directions that wind is going to whereas in the delivery model windspeeds are specified as directions that wind is coming from. Relative humidity, temperature, diurnal temperature range, wind speed precipitation and extra-terrestrial solar radiation are read from the appropriate files.

Input cloud cover data for time of day and season

Key assumption: The MODIS data represents well the pattern of atmospheric cloud, where atmospheric cloud has formed and terrain level conditions are condensing (i.e. above the cloud base), this cloud is likely to be present at ground level. MODIS derived cloud cover is read with the overall annual average value modified by seasonal and diurnal correction factors.

Temperature, dewpoint and liquid water content

Key assumption: Cloud liquid water content is proportional to absolute atmospheric humidity.

Temperature is modified according to the diurnal temperature range as follows:

```
Tmp= if(Hour eq 1 then Tmp-(0.25*DiurnalTRange) else
     if(Hour eq 2 then Tmp else
     if(Hour eq 3 then Tmp+(0.25*DiurnalTRange) else
     if(Hour eq 4 then Tmp
          ))))
```

Dewpoint and vapour pressure are calculated according to:

```
es=exp(26.66082-0.0091379024*(Tmp+273.15)-(6106.396/(Tmp+273.15)))
```

where: Tmp = temperature (C); Es = saturated vapour pressure (mb); RH = relative humidity (%); E = vapour pressure (mb)

Air density and absolute humidity are calculated as:

```
AirDensity=(MSLP*100)/((Tmp+273.15)*287)
```

Where: AirDensity = kg/m3 and MSLP = mean sea level pressure

whereby LWC varies linearly with AH under the assumption that the maximum AH observed at any one time is equivalent to the usually observed maximum LWC (0.0002 kg m3). Such a simplification is necessary because conversion of AH to LWC is complex depending on cloud condensation nuclei and cloud physics.

Dewpoint is calculated as:

```
btemp=26.66082-ln(e);
Td=((btemp-sqrt((btemp**2)-223.1986))/0.0182758048)-273.15
```

Where: Td = Celsius

Lifting condensation level

This means that the lifting condensation level (LCL) becomes

```
lcl=(1/(((Newtemp-Td)/223.15)+1)**3.5)*MSLP
```

lcl=max((44.3308-4.94654*((lcl*100)**0.190263))*1000,0)

Where: Newtemp = ground temperature (C)

The first part of Equation 10 produces the LCL in mb and the second part in masl

MSLP = mean sea level pressure (mb)

Liquid water content is distributed rather simplistically as :

LWC=(AH/mapmaximum(AH))*0.0002

SUBMODULE : precipitation

Ground level cloud (fog) occurrence

Fog occurs where the ground altitude is greater than the LCL:

fog=scalar(Dem gt lcl)

Where: Dem = elevation (m)

Fog settling

Key assumption: That fog settling occurs under calm conditions and upwards fog turbulent diffusion is limited compared with this downward flux.

Fog settling velocity is calculated according to Stokes Law based on the mean particle size for fog.

FogSettlingVel=(980*((7.5/10000)**2)*(1-0.0013))/(18*0.000185)

where 7.5 = fog droplet size in um

Forest edges

Key assumption: That forest edges are important and can be represented as catching surfaces. That, as in the Chiquito (test catchment from Mulligan and Burke (2005)), there is a random directionality of forest edges.

Forest is given an one sided LAI=3 and pasture LAI=2

Forest edges are calculated according to the tree fractional cover as :

forestedgefrac=-3E-05*Tree**2 + 0.0036*Tree forestedgelenm=forestedgefrac*((CellSize*CellSize)/(25*25))*100

emergentedgelenm=(0.05*TreeFrac)*((CellSize*CellSize)/(25*25))*100

forestedgelenfacingm=(forestedgelenm/4)

emergentedgelenfacingm=(emergentedgelenm/4)

So, that the empirical equation derived from Figure 59 (Mulligan and Burke, 2005) provides the fractional forest edge length on the basis of tree fractional cover, this is converted to an actual length based on the cell size of the grid compared with the original landsat grid. The fraction of exposed emergent trees is calculated as a 5% fractional of the area covered by tree. The division by four accounts for the fact that only one edge of a grid cell will face a wind from a particular direction.

Sedimentation surface area

Key assumption: That the whole unshaded (one sided) leaf surface area is available for sedimentation (deposition)

The surface area available for fog deposition (sedimentation) is calculated as:

ForestTrappingSfcArea=(1-(exp((-0.7*0.3*10))))

PastureTrappingSfcArea=(1-(exp((-0.7*6*0.5))))

DepositionFrac=(TreeFrac*ForestTrappingSfcArea*ForestLAI)+((1-

TreeFrac)*PastureTrappingSfcArea*PastureLAI)

Fractional trapping areas for forest and pasture are calculated first (on the basis of leaf self-shading). These are then multiplied by the fractional covers of tree and pasture for the grid cell and the available LAI.

Wind speeds modified for exposure:

Key assumption: The empirical parameters determined by Ruel (from wind tunnel studies) are representative. Exposure can be measured effectively from a DEM. Wind speeds are now modified for local wind direction dependent exposure using an approach modified from Ruel *et al.* (2002):

TanRainfallInclination=if(Prec gt 0 then windspd/DropTermVeloc else 0)

WindSlopeCorrectionfactor=if(Prec gt 0 then

1+Grad*TanRainfallInclination*cos(AspectDeg-WindDirDeg) else 0)

WindSlopeCorrectionfactor=max(WindSlopeCorrectionfactor,0)

Prec=Prec*WindSlopeCorrectionfactor

where:

Prec = monthly precipitation (mm)

Grad = slope gradient

AspectDeg = slope aspect (°)

WindDirDeg = wind direction (°)

Impaction fluxes

Key assumption: The windspeed reductions within forest and rough pasture measured at the FIESTA sites are generally representative.

Fluxes of fog available for impaction are now calculated. The model has no spatial memory or budgeting of fog so fog passing through a forest is not necessary depleted along the flowpath – rather the model assumes that there is limitless availability of fog from the near surface atmosphere (when and where fog is present) thus no budget of atmospheric moisture is maintained. Impaction fluxes are calculated as:

WindFlux=(windspd*3600)*emergentedgelenfacingm*1.5

EmergentImpactionFlux=(LWC*WindFlux)

Wind speed at the grid scale is assumed unaffected by passing through occasional emergents. 1.5 is the average height of emergents above the surrounding canopy (1.5m).

Finally the amount of water passing pasture is calculated using the correction for observed wind speeds at pasture heights and the height of pasture assumed to be 0.5 m. A fog inclination angle for fog inputs over forest and pasture is calculated, based on their respective wind speeds. A vertical flux is calculated as the fog settling velocity over the whole cell surface area (rather than any vertical catching surfaces).

The proportion of fog inputs that are deposited rather than impacted depends upon the cosine of the fog inclination angle over grassland and forest fractions.

WindFlux=(windspd*0.5030*3600)*(1-TreeFrac)*CellSize*0.5

GrassImpactionFlux=(LWC*WindFlux)

ForestFogInclinationAngle=scalar(atan((windspd*0.6053)/FogSettlingVel))

PastureFogInclinationAngle=scalar(atan((windspd*0.5030)/FogSettlingVel))

GravityFlux=(FogSettlingVel*3600)*Celltruearea

DeposProportion=((cos(ForestFogInclinationAngle))*TreeFrac)+

cos(PastureFogInclinationAngle))*(1-TreeFrac))

ImpactionProportion=1-DeposProportion

Vegetation areas for fog interception

Forest-pasture edges or boundaries are important because of their exposure to horizontal precipitation ad fog, as well as their potential to enhance these processes in fragmented landscapes (Mulligan and Burke, 2005).

Key assumption: Fog impaction occurs to all non-shaded leaves according to the geometrical relationships between the angle of incoming fog (wind speed dependent) and the leaf area. Impaction only occurs on windward forest edges whereas fog passes over forest canopies or falls as sedimentation on leeward (topographically sheltered) forests.

Next the actual intercepting area of vegetation for fog is calculated because this will be combined with the previously calculated fog fluxes in order to calculate the fog interception. Surface areas for interception depend upon the leaf area density of the vegetation and the angle of incoming fog relative to leaves. The equations are:

ForestTrappingSfcArea=(1-(exp((-

0.7*0.3*TreeFrac)/cos(ForestFogInclinationAngle))))

PastureTrappingSfcArea=(1-(exp((-0.7*6*(1-

TreeFrac))/cos(PastureFogInclinationAngle))))

ImpactionFrac=(AirRising*ForestTrappingSfcArea)

ImpactionFlux=(EmergentImpactionFlux+EdgeImpactionFlux+GrassImpactionFlux
)

SettlingFlux=LWC*GravityFlux

First the forest trapping surface area is calculated as the self-shaded area of leaves exposed to fog droplets arriving at a particular angle (for the tree fraction of the cell).

Pasture trapping surface area is calculated in a similar way (also according to pasture leaf area density and observed wind speeds).

The impaction fraction is the fraction of the total potential impaction fluxes (to emergents, to edges and to grassland) that is trapped and so depends on the calculated forest trapping surface area. Importantly impaction only occurs in the model when air is rising because the model assumes that air flows close to the ground when moving uphill (usually in windward exposed) but above the ground in the leeward, more sheltered situations slopes, the parameter air rising is true for situation where upwind elevations are greater than the downwind cell.

Ratio of impaction to sedimentation

Key assumption: the balance between impaction and deposition depends upon the fluxes of water, the tendency towards lateral or vertical flow and the intercepting areas for horizontal and vertical fluxes.

The proportional flux that will be deposited compared with that that will be impacted is calculated as:

DeposInterc=fog*(SettlingFlux*DeposProportion)*DepositionFrac

ImpactionInterc=fog*(ImpactionFlux*ImpactionProportion)*ImpactionFrac

where the ‘flux’ is the volume of water passing by the representative surface area, the ‘frac’ is the fraction of that surface area that will intercept fog and the ‘proportion’ is the proportion of the flux that is horizontal and vertical (dependent of the balance between local horizontal wind speed and settling velocity).The parameter ‘fog’ denotes areas above the LCL for that timestep so where there is no fog there will be no fog flux. The units of FogInterc, DeposInterc and ImpactionInterc are kg/m2/hr.

They are converted to mm/hr and multiplied by the cloud frequency to take account of those periods where the site may be above the LCL but no cloud generation has occurred:

FogIntmm=(FogInterc/Celltruearea)*(CloudFreqFrac)

Monthly total fluxes are the cumulation of the four monthly diurnal; fluxes and the simulation hours that they represent:

Fogtotalmm.map=Fogtotalmm.map+(FogIntmm*6*30)

SUBMODULE : evapotranspiration

See Equations 2 and 3 from Chapter 4 for the calculation of ET and water balance.

Radiation receipt and correction for cloud and fog

Key assumption: The radiation reductions observed under cloud and fog at the FIESTA sites (Mulligan and Burke, 2005) are representative for other sites also. Extra-terrestrial radiation receipts are now converted to ground level radiation receipts by correction for dimming due to the presence cloud and fog using:

TransmissionLoss=if(fog eq 1 then (CloudFreqFrac*0.678)+((1-CloudFreqFrac)*-0.143) else (CloudFreqFrac*0.525)+((1-CloudFreqFrac)*-0.143))

SolarMJ=SolarMJ*(1-TransmissionLoss)

The empirical parameters for the effect of fog and cloud on radiation receipts were taken from the analysis of the hourly radiation dataset for the pasture site. In particular the measured radiation was compared with modelled extra-terrestrial radiation for a the 1m pasture site pixel in which the weather station sits (Mulligan and Burke, 2005). The difference between modelled extra-terrestrial and received land surface radiation by hour is a function of the transmission losses by cloud and fog. Thus these transmission losses were grouped according to those periods where the pasture site fog gauges were recording fog and those when they were not. This enabled the calculation of a mean transmission loss under cloudy conditions (no fog but Rmeas<<Rmodel) and foggy conditions (fog present and Rmeas<<Rmodel).

Data were also analysed for clear conditions because the station recorded slightly lower values than the modelled values possibly because of more humid atmosphere above the station than parameterised in the atmospheric transmission component of the solar radiation model.

Net radiation

Key assumption: The solar to net radiation conversion functions measured under forest and grassland are representative for larger areas and other covers of similar density.

SolarWm=(SolarMJ*1000000)/(SecondsInMonth/2)

NetMap=((Tree/100)*(-27.9+(0.90*SolarWm)))

NetMap=NetMap+((1-(Tree/100))*(-27.5+(0.8*SolarWm)))

Again, the empirical constants for the simple linear regression of net with solar radiation for sensors above a forest and a pasture cover

Intercepted energy fractions

Key assumption: That evapotranspiration is effectively modelled at this coarse spatial and temporal scale from consideration of energy availability and atmospheric demand for water only. Leaf area is sufficient to represent plant processes and aerodynamic resistances can safely be ignored.

For simplicity and parsimony the model does not account for stomatal behaviour but rather defines the evapotranspiration differences between forest and pasture to be a function of the radiation intercepted by the canopy since this is the driver of both transpiration and wet canopy evaporation.

ExpLAI=(1-exp(-0.7*max(1,ForestLAI)))

EtFrac=TreeFrac*ExpLAI

ExpLAI=(1-exp(-0.7*max(1,PastureLAI)))

EtFrac=EtFrac+((1-(TreeFrac+BareFrac))*ExpLAI)

Thus the overall intercepted energy for ET is the sum of energy intercepted by tree leaves and by pasture in the grid cell.

Appendix III: Taxa Level Refugia compared to PAs for individual animal taxa

Figure AIII-1: Number of GCMs projecting that the PAs would contain refugia for amphibians for RCP2.6 and RCP8.5 for the 2050s

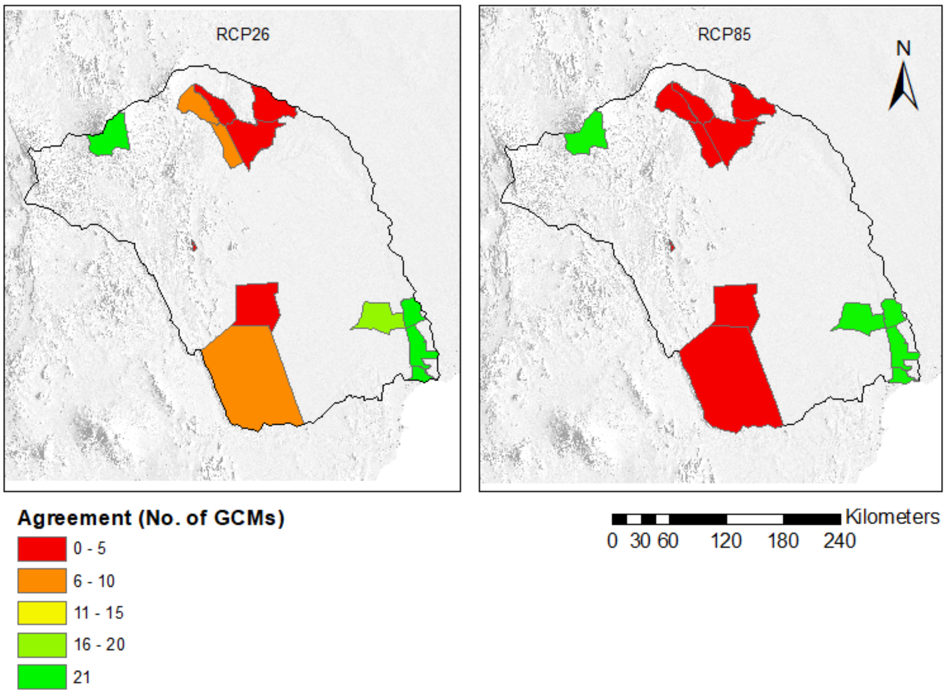


Figure AIII-2: Number of GCMs projecting that the PAs would contain refugia for reptiles for RCP2.6 and RCP8.5 for the 2050s

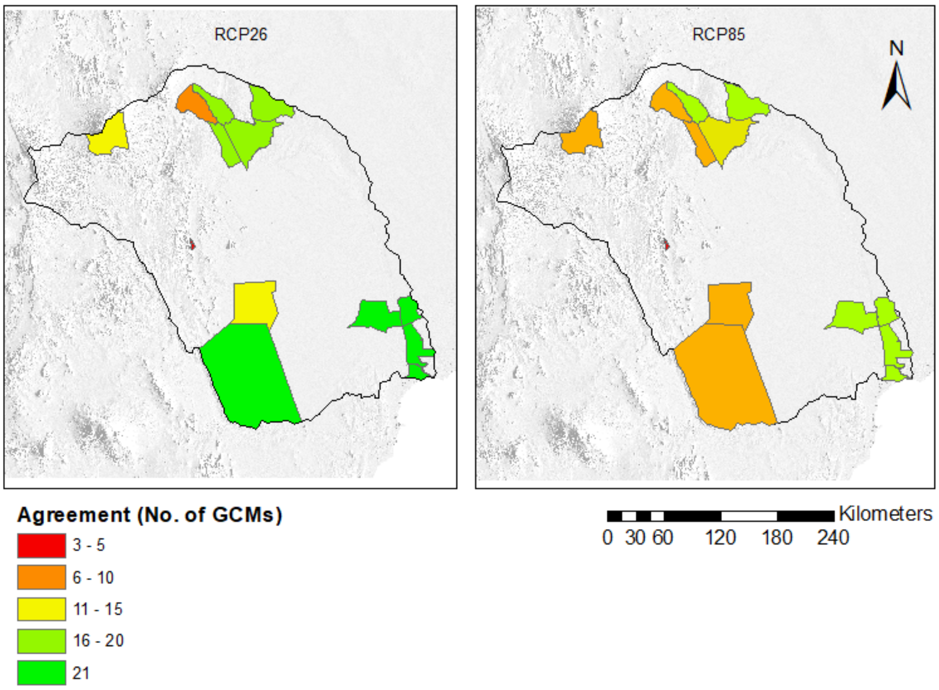


Figure AIII-3: Number of GCMs projecting that the PAs would contain refugia for birds for RCP2.6 and RCP8.5 for the 2050s, for the two dispersal scenarios

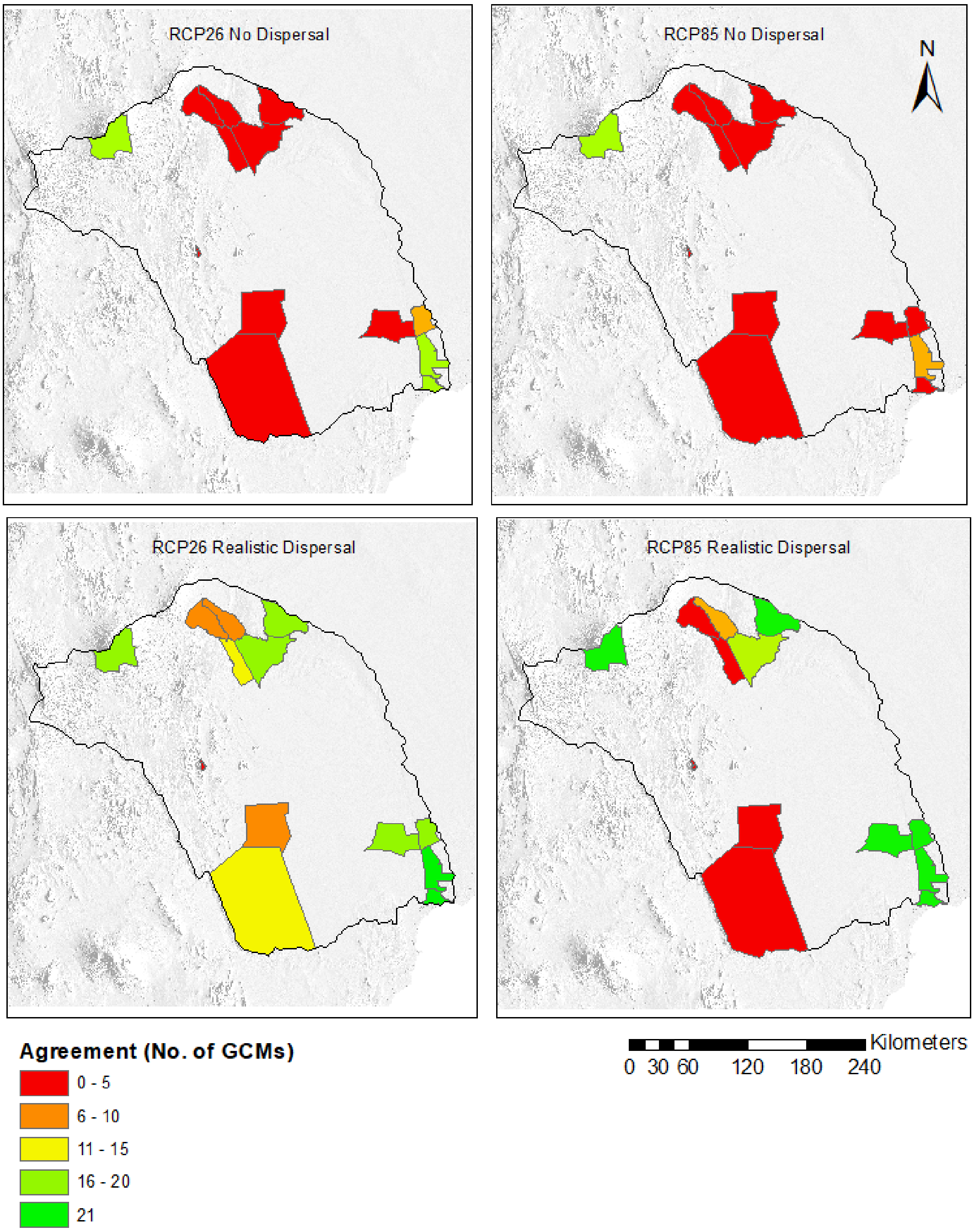
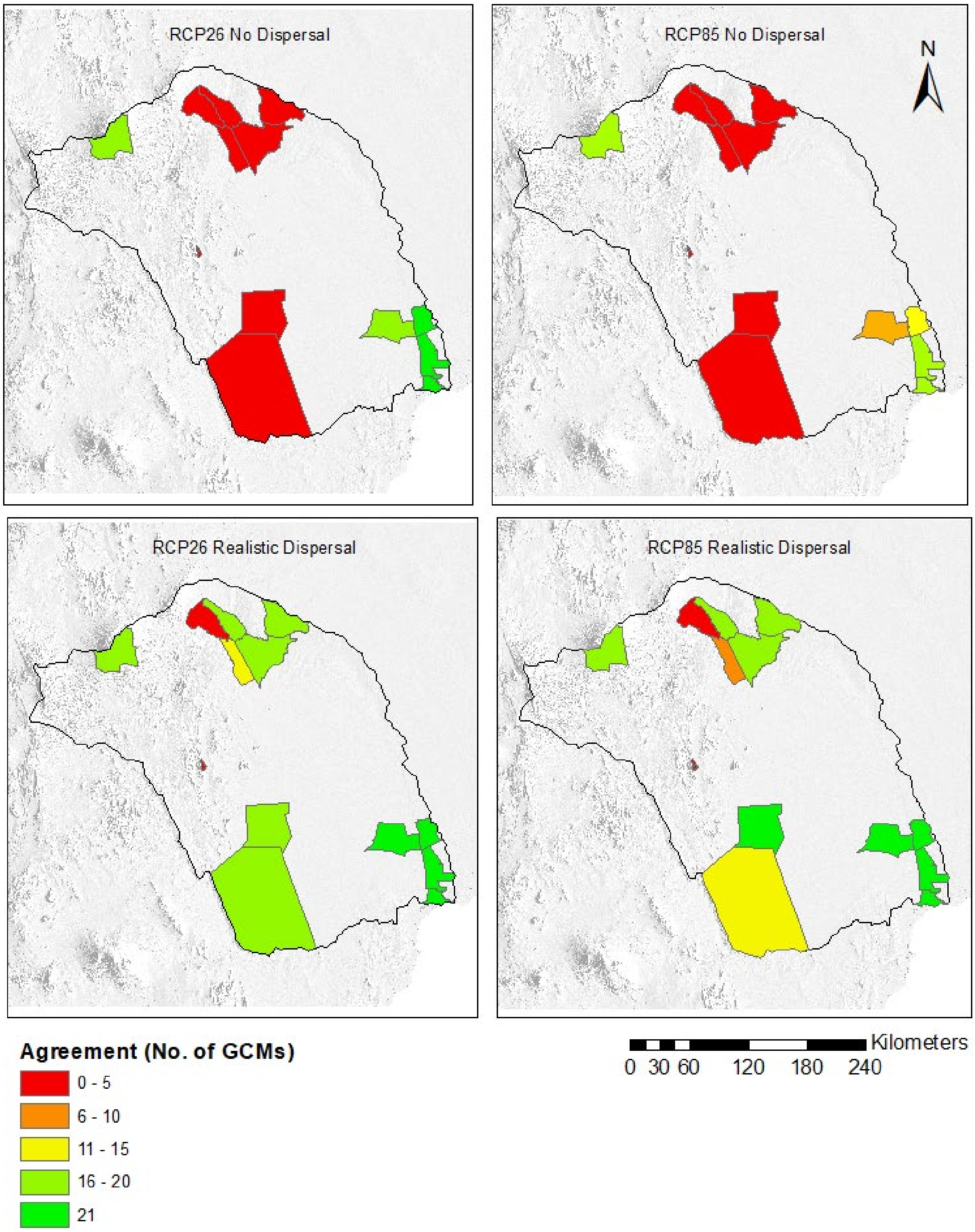


Figure AIII-4: Number of GCMs projecting that the PAs would contain refugia for mammals for RCP2.6 and RCP8.5 for the 2050s, for the two dispersal scenarios



Appendix IV: Full List of Case Study Species

Table AIV-1: Species of interest within the Tana Basin. The IUCN Red List categories relevant here are Least Concern (LC), Vulnerable (VU), Near Threatened (NT) and Endangered (EN), critically endangered (CR). '-' indicates that the species was not assessed at the time of analysis.

Taxa	Family	Genus	Species	Common names	Red List status
AMPHIBIA	*Arthroleptidae*	*Leptopelis*	*flavomaculatus*		LC
AMPHIBIA	*Hyperoliidae*	*Afrixalus*	*delicatus*	Pickersgill's Banana Frog	LC
AMPHIBIA	*Hyperoliidae*	*Hyperolius*	*argus*		LC
AMPHIBIA	*Hyperoliidae*	*Hyperolius*	*tuberilinguis*		LC
AMPHIBIA	*Pyxicephalidae*	*Pyxicephalus*	*edulis*	Lesser Bull-frog	LC
AVES	*Accipitridae*	*Aquila*	*nipalensis*	Steppe Eagle	EN
AVES	*Accipitridae*	*Circaetus*	*fasciolatus*	Southern-banded snake eagle	NT
AVES	*Accipitridae*	*Circus*	*macrourus*	Pallid Harrier, Pale Harrier	NT
AVES	*Accipitridae*	*Circus*	*pygargus*	Montagu's Harrier	LC
AVES	*Accipitridae*	*Gyps*	*africanus*	White-backed Vulture	CR
AVES	*Accipitridae*	*Necrosyrtes*	*monachus*	Hooded Vulture	CR
AVES	*Accipitridae*	*Stephanoaetus*	*coronatus*	Crowned Eagle	NT
AVES	*Accipitridae*	*Torgos*	*tracheliotos*	Lappet-faced Vulture	EN
AVES	*Accipitridae*	*Trigonoceps*	*occipitalis*	White-headed Vulture	CR
AVES	*Acrocephalidae*	*Acrocephalus*	*griseldis*	Basra Reed Warbler	EN
AVES	*Alcedinidae*	*Ceryle*	*rudis*	Pied kingfisher	LC
AVES	*Anatidae*	*Nettapus*	*auritus*	Pygmy goose	LC
AVES	*Ardeidae*	*Ardea*	*alba*	Great White Egret	LC
AVES	*Ardeidae*	*Ardeola*	*idae*	Madagascar Pond-heron	EN
AVES	*Charadriidae*	*Charadrius*	*asiaticus*	Caspian Plover	LC
AVES	*Charadriidae*	*Charadrius*	*mongolus*	Lesser Sandplover	LC
AVES	*Dicruridae*	*Dicrurus*	*modestus*	Velvet-mantled Drongo	LC
AVES	*Falconidae*	*Falco*	*chicquera*	Red-headed falcon	NT
AVES	*Gruidae*	*Balearica*	*regulorum*	Grey Crowned crane	EN

Table AIV-1

AVES	*Gruidae*	*Balearica*	*pavonina*	Black Crowned crane	VU
AVES	*Heliornithidae*	*Podica*	*senegalensis*	African finfoot	LC
AVES	*Jacanidae*	*Actophilornis*	*africanus*	African jacana	LC
AVES	*Laridae*	*Rynchops*	*flavirostris*	African Skimmer	NT
AVES	*Muscicapidae*	*Sheppardia*	*gunningi*	East Coast Akalat	NT
AVES	*Musophagidae*	*Tauraco*	*fischeri*	Fischer's Turaco	NT
AVES	*Nectariniidae*	*Anthreptes*	*reichenowi*	Plain-backed Sunbird	NT
AVES	*Pelecanidae*	*Pelecanus*	*rufescens*	Pink-backed Pelican	LC
AVES	*Phoenicopteridae*	*Phoeniconaias*	*minor*	Lesser Flamingo	NT
AVES	*Phoeniculidae*	*Phoeniculus*	*damarensis*	Violet Woodhoopoe	LC
AVES	*Scolopacidae*	*Arenaria*	*interpres*	Ruddy Turnstone, Turnstone	LC
AVES	*Scolopacidae*	*Calidris*	*alba*	Sanderling	LC
AVES	*Scolopacidae*	*Tringa*	*stagnatilis*	Marsh Sandpiper	LC
AVES	*Scolopacidae*	*Xenus*	*cinereus*	Terek Sandpiper	LC
AVES	*Struthionidae*	*Struthio*	*camelus*	Common ostrich	LC
MAMMALIA	*Bovidae*	*Damaliscus*	*lunatus*	Topi	LC
MAMMALIA	*Bovidae*	*Kobus*	*kob*	Kob	LC
MAMMALIA	*Bovidae*	*Litocranius*	*walleri*	Gerenuk	NT
MAMMALIA	*Bovidae*	*Ourebia*	*ourebi*	Oribi	LC
MAMMALIA	*Bovidae*	*Syncerus*	*caffer*	African Buffalo	LC
MAMMALIA	*Bovidae*	*Tragelaphus*	*imberbis*	Lesser Kudu	NT
MAMMALIA	*Canidae*	*Lycaon*	*pictus*	African wild dog	EN
MAMMALIA	*Cercopithecidae*	*Cercopithecus*	*mitis*	Sykes' monkey	LC
MAMMALIA	*Cercopithecidae*	*Erythrocebus*	*patas*	Patas Monkey	LC
MAMMALIA	*Elephantidae*	*Loxodonta*	*africana*	African elephant	VU

MAMMALIA	*Felidae*	*Acinonyx*	*jubatus*	Cheetah	VU
MAMMALIA	*Felidae*	*Leptailurus*	*serval*	Serval	LC
MAMMALIA	*Felidae*	*Panthera*	*leo*	African lion	VU
MAMMALIA	*Felidae*	*Panthera*	*pardus*	Leopard	VU
MAMMALIA	*Giraffidae*	*Giraffa*	*camelopardalis*	Giraffe	VU
MAMMALIA	*Herpestidae*	*Atilax*	*paludinosus*	Marsh mongoose	LC
MAMMALIA	*Hippopotamidae*	*Hippopotamus*	*amphibius*	Hippo	VU
MAMMALIA	*Hipposideridae*	*Hipposideros*	*vittatus*	Commerson's Leafnosed Bat	NT
MAMMALIA	*Molossidae*	*Otomops*	*martiensseni*	Large-eared Free-tailed Bat	NT
MAMMALIA	*Mustelidae*	*Aonyx*	*capensis*	African clawless otter	NT
MAMMALIA	*Mustelidae*	*Hydrictis*	*maculicollis*	Spotted-necked Otter	NT
MAMMALIA	*Pteropodidae*	*Eidolon*	*helvum*	African Straw-coloured Fruit-bat	NT
PLANTAE	*Annonaceae*	*Mkilua*	*fragrans*		VU
PLANTAE	*Annonaceae*	*Uvariodendron*	*gorgonis*		EN
PLANTAE	*Araceae*	*Gonatopus*	*petiolulatus*		VU
PLANTAE	*Arecaceae*	*Phoenix*	*reclinata*	Wild date palm	LC
PLANTAE	*Asteraceae*	*Brachylaena*	*huillensis*		LR/nt
PLANTAE	*Buxaceae*	*Buxus*	*obtusifolia*		VU
PLANTAE	*Combretaceae*	*Pteleopsis*	*tetraptera*		LR/nt
PLANTAE	*Connaraceae*	*Ellipanthus*	*hemandradenioides*		LR/nt
PLANTAE	*Cornaceae*	*Alangium*	*salviifolium*	Sage-leaved alangium	-
PLANTAE	*Ebenaceae*	*Diospyros*	*shimbaensis*		EN
PLANTAE	*Ebenaceae*	*Diospyros*	*greenwayi*		VU
PLANTAE	*Ebenaceae*	*Diospyros*	*mespiliformis*	Jackalberry	-
PLANTAE	*Euphorbiaceae*	*Aristogeitonia*	*monophylla*		VU

Table AIV-1

PLANTAE	*Fabaceae*	*Cynometra*	*suaheliensis*		VU
PLANTAE	*Fabaceae*	*Cynometra*	*webberi*		VU
PLANTAE	*Fabaceae*	*Dalbergia*	*bracteolata*		LR/nt
PLANTAE	*Fabaceae*	*Dialium*	*orientale*		LR/nt
PLANTAE	*Fabaceae*	*Julbernardia*	*magnistipulata*		VU
PLANTAE	*Fabaceae*	*Newtonia*	*erlangeri*		EN
PLANTAE	*Gesneriaceae*	*Saintpaulia*	*ionantha*		NT
PLANTAE	*Loranthaceae*	*Oncella*	*curviramea*		VU
PLANTAE	*Lythraceae*	*Nesaea*	*pedicellata*		VU
PLANTAE	*Melastomataceae*	*Warneckea*	*amaniensis*		VU
PLANTAE	*Moraceae*	*Ficus*	*sycomorus*	Sycamore fig	-
PLANTAE	*Moraceae*	*Milicia*	*excelsa*		LR/nt
PLANTAE	*Pandanaceae*	*Pandanus*	*rabaiensis*		NT
PLANTAE	*Rubiaceae*	*Afrocanthium*	*kilifiense*		VU
PLANTAE	*Rubiaceae*	*Gardenia*	*transvenulosa*		VU
PLANTAE	*Rubiaceae*	*Kraussia*	*speciosa*		VU
PLANTAE	*Rubiaceae*	*Psydrax*	*faulknerae*		VU
PLANTAE	*Salicaceae*	*Oncoba*	*spinosa*	Snuff-box tree	-
REPTILIA	*Cheloniidae*	*Chelonia*	*mydas*	Green Turtle	EN
REPTILIA	*Cheloniidae*	*Eretmochelys*	*imbricata*	Hawksbill Turtle	CR
REPTILIA	*Colubridae*	*Dasypeltis*	*scabra*	Rhombic Egg Eater	LC
REPTILIA	*Trionychidae*	*Trionyx*	*triunguis*	African Softshell Turtle	VU

Appendix V: Additional Results of the Case Study Species Analysis from Chapter 5

Reptiles

Climate completely unsuitable by 4.5°C

- African softshell turtle (*Trionyx triunguis*)

Plants

Climate completely unsuitable by 4.5°C

- *Cynometra webberi*
- *Gardenia transvenulosa*
- *Psydrax faulknerae*
- *Pteleopsis tetraptera*
- *Saintpaulia ionantha*
- *Brachylaena huillensis*

Birds (No Dispersal)

Climate completely unsuitable by 4.5°C

- Steppe eagle (*Aquila nipalensis*)
- Pallid harrier (*Circus macrourus*)
- Sanderling (*Calidris alba*)
- Violet wood hoopoe (*Phoeniculus damarensis*)
- Montagu's harrier (*Circus pygargus*)
- East Coast Akalat (*Sheppardia gunningi*)
- *Basra reed warbler (Acrocephalus griseldis)*

Climate largely unsuitable by 2°C (10 cells or fewer remaining suitable within the basin)

- Violet wood hoopoe (*Phoeniculus damarensis*)
- White-backed vulture (*Gyps africanus*)
- Basra reed warbler (*Acrocephalus griseldis*)
- Steppe eagle (*Aquila nipalensis*)
- Montagu's harrier (*Circus pygargus*)
- Pallid harrier (*Circus macrourus*)
- *African finfoot (Podica senegalensis)*

Birds (Realistic Dispersal)

Climate completely unsuitable by 4.5°C

- Sanderling (*Calidris alba*)
- Steppe eagle (*Aquila nipalensis*)

- Violet wood hoopoe (*Phoeniculus damarensis*)
- Montagu's harrier (*Circus pygargus*)
- White-backed vulture (*Gyps africanus*)
- Pallid harrier (*Circus macrourus*)
- Basra reed warbler (*Acrocephalus griseldis*)
- East Coast Akalat (*Sheppardia gunningi*)

Climate largely unsuitable by 2°C (10 cells or fewer remaining suitable within the basin)

- Steppe eagle (*Aquila nipalensis*)
- Violet wood hoopoe (*Phoeniculus damarensis*)
- Montagu's harrier (*Circus pygargus*)

Climate becoming more suitable with 2°C

- African pygmy goose (*Nettapus auritus*)
- African finfoot (*Podica senegalensis*)
- Terek sandpiper (*Xenus cinereus*)
- Lesser sand plover (*Charadrius mongolus*)
- African skimmer (*Rynchops flavirostris*)
- Black crowned crane (*Balearica pavonina*)
- Hooded vulture (*Necrosyrtes monachus*)
- Great egret (*Ardea alba*)
- Madagascar Pond-heron (*Ardeola idea*)
- Velvet-mantled drongo *(Dicrurus modestus)*

Climate becoming more suitable with 4.5°C

- African pygmy goose (*Nettapus auritus*)
- African skimmer (*Rynchops flavirostris*)
- African finfoot (*Podica senegalensis*)
- African jacana (*Actophilornis africanus*)
- Black crowned crane *(Balearica pavonina)*

Mammals (No Dispersal)

Climate completely unsuitable by 4.5°C

- African wild dog (*Lycaon pictus*)

Climate largely unsuitable by 2°C (10 cells or fewer remaining suitable within the basin)

- Topi (*Damaliscus lunatus*)

Mammals (Realistic Dispersal)

Climate completely unsuitable by 4.5°C

- African wild dog (*Lycaon pictus*)

Climate largely unsuitable by 2°C (10 cells or fewer remaining suitable within the basin)

- Topi (*Damaliscus lunatus*)

Climate becoming more suitable

- Patas monkey (*Erythrocebus patas*)
- Marsh mongoose (*Atilax paludinosus*)
- Straw-coloured fruit bat (*Eidolon helvum*)
- African clawless otter (*Aonyx capensis*)
- Striped leaf-nosed bat (*Hipposideros vittatus*)
- Kob (*Kobus kob*)
- Oribi (*Ourebia ourebi*)
- Serval (*Leptailurus serval*)
- Spotted-necked otter *(Hydrictis maculicollis)*

Table AV-1: Proportions of the current suitable area remaining suitable for the case study mammals with 2°C and 4.5°C warming, without dispersal

Mammals – No Dispersal		
	Percentage of current area suitable remaining with 2°C	Percentage of current area suitable remaining with 4.5°C
Hipposideros vittatus	100	98
Kobus kob	100	100
Erythrocebus patas	100	100
Hydrictis maculicollis	100	100
Atilax paludinosus	100	92
Ourebia ourebi	97	89
Litocranius walleri	96	91
Leptailurus serval	95	89
Cercopithecus mitis	93	81
Aonyx capensis	90	85
Eidolon helvum	89	60
Tragelaphus imberbis	82	12
Panthera pardus	74	11
Otomops martiensseni	70	5
Lycaon pictus	63	0
Syncerus caffer	55	59
Hippopotamus amphibius	54	11
Loxodonta africana	51	17
Giraffa camelopardis	50	6
Panthera leo	43	3
Acinonyx jubatus	32	2
Damaliscus lunatus	18	5

Table AV-2: Proportions of the current suitable area remaining suitable for the case study mammals with 2°C and 4.5°C warming, with realistic dispersal

Mammals – Realistic Dispersal		
	Percentage of current area suitable remaining with 2°C	Percentage of current area suitable remaining with 4.5°C
Erythrocebus patas	646	781
Atilax-paludinosus	633	1000
Eidolon helvum	243	331
Aonyx-capensis	236	356
Hipposideros vittatus	185	238
Kobus kob	141	205
Ourebia ourebi	137	184
Leptailurus-serval	132	199
Hydrictis maculicollis	123	161
Cercopithecus-mitis	98	82
Litocranius-walleri	96	91
Tragelaphus imberbis	82	12
Loxodonta-africana	81	31
Syncerus-caffer	76	103
Panthera-pardus	74	11
Panthera-leo	72	3
Otomops martiensseni	70	5
Hippopotamus-amphibius	68	37
Giraffa-camelopardis	66	9
Lycaon-pictus	63	0
Acinonyx-jubatus	34	2
Damaliscus-lunatus	18	5

Table AV-3: Proportions of the current suitable area remaining suitable for the case study amphibians and reptiles with 2°C and 4.5°C warming

Reptiles and Amphibians		
	Percentage of current area suitable remaining with 2°C	Percentage of current area suitable remaining with 4.5°C
Chelonia mydas	68	36
Eretmochelys imbricata	56	31
Trionyx triunguis	38	0
Dasypeltis scabra	95	90
Hyperolius argus	81	21
Hyperolius tuberilinguis	96	43
Leptopelis flavomaculatus	92	56
Pyxicephalus edulis	100	100
Afrixalus delicatus	90	57

Table AV-4: Proportions of the current suitable area remaining suitable for the case study plants with 2°C and 4.5°C warming

Plants		
	Percentage of current area suitable remaining with 2°C	Percentage of current area suitable remaining with 4.5°C
Diospyros shimbaensis	100	95
Newtonia erlangeri	100	90
Uvariodendron gorgonis	91	69
Afrocanthium kilifiense	100	86
Aristogeitonia monophylla	100	89
Buxus obtusifolia	87	55
Cynometra suaheliensis	100	87
Cynometra webberi	58	0
Dalbergia bracteolata	85	52
Dialium orientale	100	100
Diospyros greenwayi	100	90
Ellipanthus hemandradenioides	100	88
Gardenia transvenulosa	22	0
Gonatopus petiolulatus	100	84
Julbernardia magnistipulata	91	55
Kraussia speciosa	97	79
Milicia excelsa	90	94
Mkilua fragrans	90	42
Nesaea pedicellata	100	99
Oncella curviramea	99	87
Pandanus rabaiensis	92	66
Psydrax faulknerae	46	0
Pteleopsis tetraptera	69	0
Saintpaulia ionantha	52	0
Warneckea amaniensis	90	63
Brachylaena huillensis	61	0

Table AV-5: Proportions of the current suitable area remaining suitable for the case study birds with 2°C and 4.5°C warming, without dispersal

Birds – No Dispersal		
	Percentage of current area suitable remaining with 2°C	Percentage of current area suitable remaining with 4.5°C
Dicrurus modestus	100	65
Podica senegalensis	100	89
Necrosyrtes monachus	96	84
Balearica pavonina	96	91
Circaetus fasciolatus	96	73
Anthreptes reichenowi	94	67
Tauraco fischeri	85	46
Ardeola idae	83	32
Actophilornis africanus	81	76
Nettapus auritus	81	56
Falco chiquera	77	18
Trigonoceps occipitalis	72	2
Ceryle rudis	72	40
Ardea alba	71	18
Xenus cinereus	66	51
Charadrius mongolus	58	50
Tringa stagnatilis	57	47
Balearica regulorum	56	11
Arenaria interpres	55	20
Pelecanus rufescens	49	60
Calidris alba	47	0
Charadrius asiaticus	47	66
Rynchops flavirostris	46	37
Stephanoaetus coronatus	41	26
Phoeniconaias minor	39	42
Sheppardia gunningi	39	0
Struthio camelus	36	1
Torgos tracheliotus	24	1
Circus macrourus	23	0
Circus pygargus	13	0
Aquila nipalensis	12	0
Gyps africanus	7	3
Acrocephalus griseldis	6	0
Phoeniculus damarensis	2	0

Table AV-6: Proportions of the current suitable area remaining suitable for the case study birds with 2°C and 4.5°C warming, with realistic dispersal

Birds – Realistic Dispersal		
	Percentage of current area suitable remaining with 2°C	Percentage of current area suitable remaining with 4.5°C
Nettapus auritus	338	650
Podica senegalensis	222	267
Xenus cinereus	171	68
Charadrius mongolus	135	54
Rynchops flavirostris	115	322
Balearica pavonina	110	110
Necrosyrtes monachus	109	100
Ardea alba	108	20
Ardeola idae	108	48
Dicrurus modestus	102	67
Actophilornis africanus	100	173
Circaetus fasciolatus	97	73
Anthreptes reichenowi	94	67
Tringa stagnatilis	89	50
Tauraco fischeri	87	48
Falco chiquera	84	23
Trigonoceps occipitalis	79	2
Ceryle rudis	73	53
Arenaria interpres	57	20
Balearica regulorum	56	11
Pelecanus rufescens	54	83
Gyps africanus	53	0
Stephanoaetus coronatus	50	26
Calidris alba	49	0
Charadrius asiaticus	47	71
Phoeniconaias minor	41	47
Sheppardia gunningi	39	0
Struthio camelus	36	1
Circus macrourus	35	0
Torgos tracheliotus	24	1
Circus pygargus	17	0
Aquila nipalensis	13	0
Acrocephalus griseldis	13	0
Phoeniculus damarensis	2	0

Appendix VI: Key Characteristics of the ISI-MIP FT Global Crop Models

Table AVI-1: Summary of the key characteristics, inputs and agricultural management practices in the GGCMs from the ISI-MIP Fast Track database used within this research. Adapted from Rosenzweig et al. (2014) supplementary appendix.

Model	Model Origin	Temporal Scale [1]	Input Climate Variables [2]	CO_2 concentration baseline (+ year)	CO_2 Effects Method [3]	Planting date decisions [4]	Fertiliser Application [5]	ET Calc. [6]	Adaptation	Output	Calibration
EPIC	Site-based	D, H	Tmn, Tmx, P, Rad, RH, WS	380 ppm (2005)	RUE TE	S	Automatic N input, dynamic application	PM	Adjustment of planting dates	Yield	Site-specific
GEPIC	Site-based	D	Tmn, Tmx, P, Rad, RH, WS	364 ppm (2000)	RUE TE	S, Clim. Adapt	NP, dynamic application	PM	Decadal adjustment of planting dates	Yield	Site-specific and global
IMAGE	GAEZ	M, WG	Ta, P	370 ppm (2000)	RUE	Clim. Adapt	N/A	PT	Dynamic planting window	Potential Yield	N/A
LPJmL	Ecosystem	D	Ta, P, cld (or Rad)	370 ppm (2000)	LF, SC	S	N/A	PT	Fixed sowing dates	Yield	Global
pDSSAT	Site-based	D	Tmn, Tmx, P, Rad	330 ppm (1975)	RUE, TE	S	SPAM, dynamic application	PT	No adjustment	Yield	Site-specific
PEGASUS	Ecosystem	D	Ta, Tmn, Tmx, P, cld (or sun)	369 ppm (2000)	RUE TE	S, Clim Adapt.	NPK, annual application	PT	Adjustment of planting dates; variable heat units to reach maturity	Yield	Global

Notes:

(1) Temporal scale: H: hourly; D: daily; M: monthly; WG: weather generator

(2) Input climate variables: Ta: average temperature, Tmn: minimum temperature, Tmx: maximum temperature, cld: percentage of cloud cover, sun: fraction of sunshine hours; RH: relative humidity; WS: wind speed

(3) Elevated CO_2 effects: LF: Leaf-level photosynthesis (via rubisco or quantum-efficiency and leaf-photosynthesis saturation; RUE: Radiation use efficiency; TE: Transpiration efficiency; SC: stomatal conductance

(4) Planting date decisions: S: simulate planting dates according to climatic conditions; Clim adapt: dynamic planting window (adaptation to climate change)

(5) Fertiliser application, timing of application; NPK annual application of total NPK (nutrient-stress factor); source of fertiliser application data; timing: annual or dynamic SPAM: Spatial Production Allocation Model

(6) ET Calculation Method: PM: Penman – Monteith; PT: Priestley –Taylor