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Full length Research paper

Climate change impacts on land use in Gadaref and North Kordofan States and future Desert sheep distribution in Sudan

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Trends of TMIN, TMAX and rainfall anomalies in Gadaref and North Kordofan States, Sudan, were analyzed for 1981-2017. Vegetation biomass was measured and regressed with NDVI. Crop residues and feed concentrates quantities were also obtained and livestock carrying capacities and stocking rates calculated. Further, an optimistic (RCP 2.6) and a rather pessimistic (RCP 8.5) climate scenarios were presented to analyze future distribution of Desert sheep in Sudan. Rainfall anomalies reflected frequent droughts, with high inter-annual variability. There were positive trends for both TMIN and TMAX in Gadaref State, indicating a 0.5ºC decadal increase. In North Kordofan, only TMIN showed a positive trend. In Gadaref, rangeland area was reduced from 48% of the total State area in 1990 to 23% in 2017, while the respective decrease in North Kordofan was from 51.5% to 49.9%. Both States were in negative feed balance, being worser in North Kordofan with about 2.4 folds overstocking. Climate change pessimistic scenario (RCP 8.5) for Desert sheep distribution indicated a reduction in suitable areas,that would be confined to the southern and coastal zones. Gadaref and North Kordofan States are most vulnerable to climate change. Correct management of livestock could play important roles in both mitigation and adaptation.

Key words: biomass production, climate change scenarios, drylands, Desert sheep distribution, land use, rainfall anomalies, temperature trends

INTRODUCTION

Rangelands provide great ecosystem functions and services, support wildlife, and have long been places for users including pastoralists and their livestock (Getabalew and Alemneh, 2019). African ecosystems are already being affected by climate change, and future impacts are expected to be substantial (IPCC, 2014). However, dryland ecosystems are projected to experience more frequent and intensified drought and land-use changes (Yao et al., 2020). The climatic

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characteristics are severe and unpredictable, causing a strong seasonality in grassland production (Sautier et al., 2013), and grasses nutritional quality, which are both adversely affected by abiotic and biotic environmental factors including climatic regime (Meshesha et al., 2019) and soil type. This is reflected in declines in tree density and changes in species composition (IPCC, 2014).In semiarid areas biomass production and the quality of the grassland varies with temporal and spatial gradients (McGranahan et al., 2016), producing a complex environment which is difficult to manage for optimal livestock production. Climate change may affect the livelihoods, food security, and health of vulnerable people through its effects on livestock and livestock systems, such as changes in water and feed availability (Welsh, 2021).

Globally, based on changes in herbaceous production, grazing livestock are projected to decline by 7.5 to 9.6% of total stocking in rangelands. These declines are most palpable in savannas south of the Sahara, where declining forage and browse production present significant climate-induced threats to rangeland production systems (Boone et al., 2018). With climate change bound to affect food and feed production, emphasis will shift to resilient and adapted indigenous livestock to sustain animal production (Abied et al., 2021). There is a high need to identify rangeland-livestock systems vulnerable to climate changes (McCollum et al., 2018). The objectives of this study were to assess indicators of climate change and their impacts on land use, particularly, rangelands in North Kordofan and Gadaref States. Further, the study speculated the possible future distribution scenarios of Sudan Desert sheep in Sudan.

MATERIALS AND METHODS

Study area: This study was conducted in the States of Gadaref in eastern Sudan and North Kordofan in western Sudan. Gadaref State (lat.12˚48'-15˚50'N, longit. 33˚40'-36˚47'E), covers an area of about 6.2 million ha (62,257.95 km^2) (Yagoub et al., 2017), whereas North Kordofan State (lat. 11º15’-16º45'N; longitudes 27º05’-32º00’E), covers an area of about18.4 million ha(188,140 km^2) (Mohamed et al., 2014).

Based on average annual rainfall, potential evapotranspiration and according to the ratio of humid to arid months and length of the growing season (Yousif et al., 2018), the study area could be broadly divided into three agroclimatic zones; semidesert, arid and semiarid. In the Semidesert zone, rainfall ranges from 100-200 mm/year with duration of the growing season of 30 to less than 60 days. This short growing season and the low unreliable rainfall are major risks to agricultural production. In the Arid zone, rainfall ranges from 200-350 mm/year with duration of the growing season from 60 to less than 90 days. The erratic nature of the rainfall and the short duration of the season make crop production extremely risky in this zone. Climatically, the area is more suitable for livestock production than for cultivation of crops, as being an important source for grazing and browsing for pastoral and agropastoral herds. In the Semiarid zone, rainfall varies from 350 to 750 mm/year, with growing season duration of 90 to less than 120 days. The cultivated crops depend upon erratic and variable rains.

Climate variability and characteristics:

Monthly maximum (TMAX), minimum (TMIN) temperatures, and rainfall data from 1981 to 2017 were collected. Annual averages TMIN, TMAX, and rainfall, were calculated from the monthly data (Salehnia et al., 2017). A linear regression analysis was performed for the relatively wet months and annual averages to determine the annual and monthly trends of TMIN and TMAX and precipitation (May-October). Rainfall anomalies were computed from the long-term average (1981-2017) to understand rainfall patterns and variability (Salehnia et al., 2017). The variability, as the difference between total rainfall for each year/season, and the long-term mean (LTM) was divided by standard deviation to derive the annual rainfall anomalies (Hansel et al., 2016).

Biomass assessment:

This was done annually during 2000-2017. At each State, three sites were chosen to represent the three agroclimatic zones to ensure evaluation of the relationships between vegetation indices and biomass (Dingaan and Tsubo, 2019) in a wide range of conditions during the rainy season. The sampling plot comprised 250x250m^2; equivalent to one pixel of MODIS NDVI images, based on locating randomly 60 nested quadrates (10x10m^2 and 1x1m^2). At each nested quadrate, the tree biomass was assessed in 10x10m^2 (Hernandez, 2004), while grass biomass was assessed in a 1x1m^2. Fodder foliage was calculated as 10% of total tree biomass in the Sahel zone (Diouf et al., 2015).

In addition to grasses biomass, residues of various crops, concentrates of sesame and groundnut and sorghum grains were obtained from cultivated land. These data were obtained from government statistics (Ministry of Agriculture and Natural Resources [MOA], 2000-2017). Then, livestock carrying capacities and stocking rates for North Kordofan, and Gadaref States were calculated. A daily dry matter disappearance rate of 7.5 kg/ha was attributed to one tropical livestock unit (TLU) per day. One TLU is equivalent to 250 kg live weight (Rothman-Ostrow et al., 2020). Carrying capacity was expressed as number of hectares needed to support one TLU for one year (ha/TLU/year), whereas the stocking rate expressed the actual number of animals on a management unit throughout the time period of grazing (SRM, 1989).

Potential impact of climate change on Desert sheep future distribution in Sudan:

Two climate models were used to formulate the predictions: the Hadley Global Environment Model 2 Earth System (HadGEM2-ES) (Collins et al., 2008), and the Institute Pierre Simon Laplace Coupled Model 5 LR (IPSL-CM5-LR) (Dufresne et al., 2013). For each model, two Representative Concentration Pathway (RCP) scenarios are presented: one optimistic (RCP 2.6) and one rather pessimistic (RCP 8.5). This analysis used a scaling down approach (from global to local) to analyze the climate effects on vegetation, land, soil, and distribution of Desert sheep in Sudan (FAO, 2020), using Breed Distribution Model (BDM). BDM is useful for both international and local breeds, but it is particularly useful for local breeds kept mainly under extensive conditions (FAO, 2020)such as the local Sudanese Desert sheep.

RESULTS AND DISCUSSION

Climate Variability:

In Africa, precipitation amounts are likely to decrease for most parts of Sub-Saharan Africa (SSA) while rainfall variability is expected to increase (IPCC, 2014). Annual rainfall anomalies, from 1981 to 2017 in Gadaref and North Kordofan States (Figure 1), reflected that drought seemed to be frequent in Gadaref state during the period from 1981 to 2017.Experienced moderate to severe droughts in 1983, 1984,1987,1990,1991, 2011, and 2015 had below average rainfall. Conversely, the highest yearly rainfall was in 2013 and 2014. In North Kordofan, droughts were frequent in the decade of 1981-1991 and less frequent in the decade of 2001-2011, with high inter-annual variability. It was observed that rainfall was above average for the three consecutive years of 2006, 2007 and 2008 in Gadaref State while in North Kordofan, highest yearly rainfall was in 1998, 2006 and2008.In Sudan, drought is one of the most prevalent climate change-related natural hazards affecting the country (Elagib, 2015). Repeated droughts form the main threat to rural livelihoods and food security (Mohmmed et al., 2018).

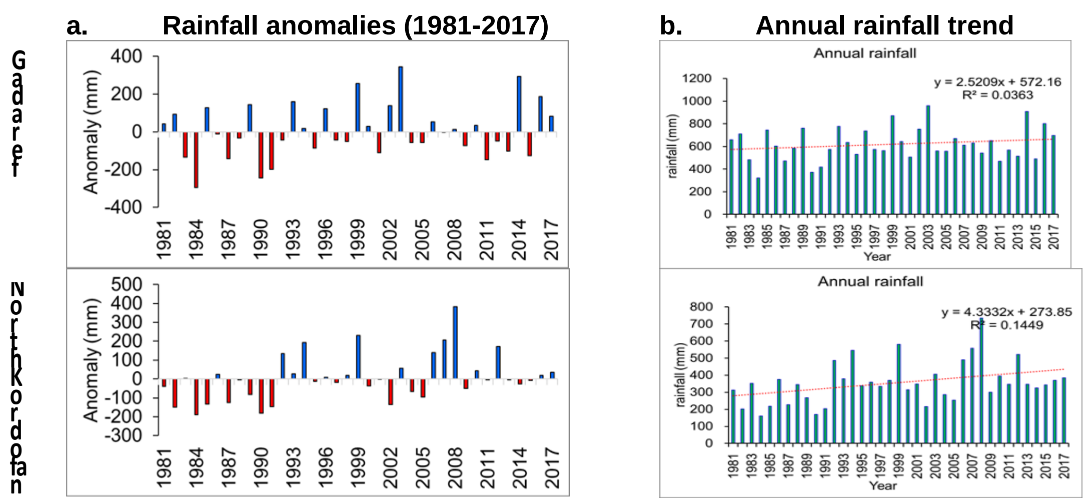

Figure 1: Anomalies of annual rainfall (mm) and rainfall trendfrom 1981 to 2017 in Gedaref and North Kordofan States.

The linear regression of annual minimum (TMIN) and maximum (TMAX) temperatures (Figure 2) trends from 1981 to 2017 at Gadaref meteorological station disclosed a positive trend for both TMIN and TMAX. The linear regression slope of TMIN was higher compared to TMAX indicating a faster increase of 0.5ºC per decade in Gadaref state. Monthly TMIN had positive trends in May, June, July, August, September, and October ($P \leq 0.05$) (Table 1). In North Kordofan, only TMIN showed a positive trend, but no trend for TMAX (Table 1). Elhag and Zhang (2018) calculated average change in temperature from 2001-2011 in Sudan, suggested an increase of 0.3ºC.Gil-Alana et al. (2019) stated that temperature tends to increase over Sub-Saharan Africa while Elagib (2010) studying trends in intra-and inter-annual temperature variabilities across Sudan found the increase was more pronounced in arid zones.

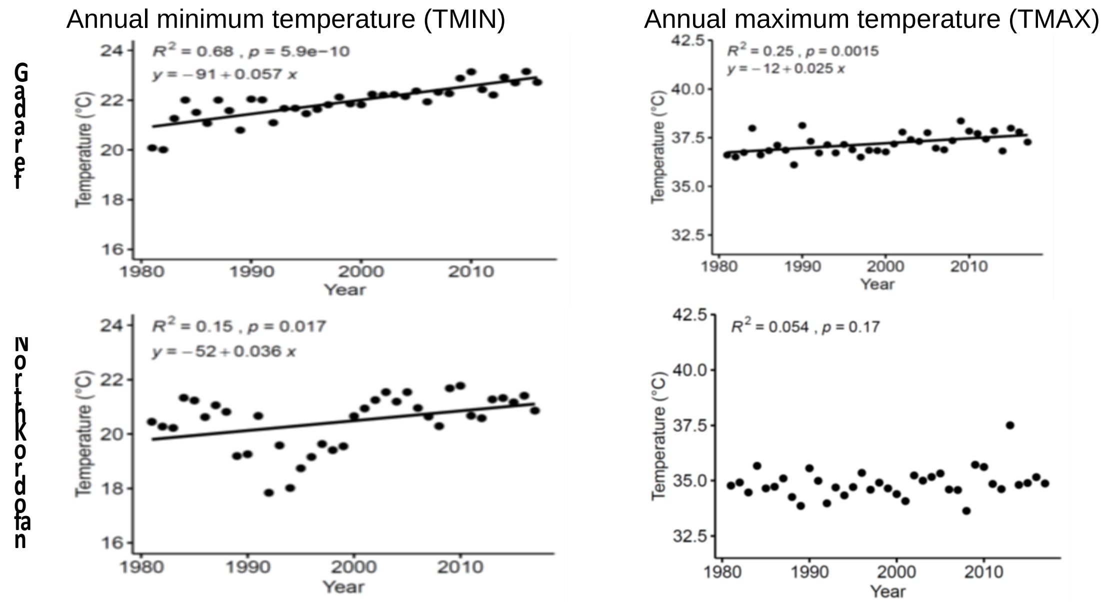

Figure 2: Minimum (TMIN) and Maximum (TMAX) temperatures (° C) from 1981 to 2017 in Gadaref and North Kordofan States.

Table 1: Monthly rainfall and NDVI data and monthly minimum (TMIN) and maximum (TMAX) temperature trends for the period 2000-2017 in Gadaref and North Kordofan States, Sudan

MONTH	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**
Gadaref State							
NDVI	0.155512	0.167776	0.190168	0.207888	0.218911	0.21476	0.201312
Rainfall	8.8	22.3	69.4	167	210	98.5	27.5
	Statistics	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Monthly minimum Temp. linear trends	p-value	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
	r- square	0.4	0.24	0.35	0.21	0.3	0.31
	Slope	0.06	0.05	0.05	0.02	0.04	0.04
Monthly maximum temp. linear trends	p-value	0.09	0.02	0.25	0.36	0.61	0.85
	r- square	0.08	0.15	0.04	0.02	0.01	<0.01
	Slope	0.03	0.04	0.02	-0.02	-0.01	<0.01
North Kordofan State							
NDVI	0.156512	0.168776	0.190268	0.208888	0.218911	0.214976	0.202312
Rainfall	1.6	14.3	46.3	66.5	67.9	51.2	27.7
Temperature	**Statistics**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Monthly minimum linear trend	p-value	0.11	0.53	0.52	0.51	0.3	0.56
	r- square	0.07	0.01	0.01	0.01	0.03	0.01
	Slope	0.03	0.01	0.01	0.01	0.02	0.01
Monthly maximum linear trend	p-value	0.64	0.93	0.28	<0.01	0.05	0.51
	r- square	0.01	<0.01	0.03	0.31	0.11	0.01
	Slope	0.01	<0.01	-0.03	-0.1	-0.04	0.01

Pearson correlation of NDVI and Rainfall = 0.789 (P<0.000) for Gadaref State, and = 0.899 (P<0.006) for North Kordofan State

Changes in Land Use in 1990 and 2017:

In Gadaref State, in 1990, rangelands represented 48% of the total State area, whereas in 2017, rangeland areas were reduced sharply to 23%. The reduction in range area was mainly due to an increase in agricultural areas from 37% in 1990 to 62% in 2017 (Table 2). In total, Gadaref State has around 4.2 million ha of cultivable land at its disposal (MFC, 2012). Much of this land was originally mixed savannah-woodland providing grazing lands for pastoralists. However, there is a conspicuous shift from livestock production to crop farming (Sulieman, 2015). The current land tenure system has created a situation of a few large-scale farmers and many small-scale ones, as well as restricting livestock herders to the marginal areas of the State (Glover, 2005). In North Kordofan State, rangelands area in 1990 was estimated at 9,449,310 ha (51.5% of total land area), by 2017 reduced to 9,152,200 ha (49.9% total land area) (Table2). Mohamed et al. (2014) studied land use and land cover (LULC) changes in North Kordofan during 1973-2001, using remote sensed data analysis. They demonstrated different signs of desertification in the study area related to changed patterns in LULC classes, such as increase in farms at the expense of wood and grasslands, and that during the drought of 1984-85 most of the woody cover disappeared from the northern part of the State.

Table 2: Land use changes (000, ha) between 1990 and 2017 in Gadaref and North Kordofan States, Sudan

Land use	1990	As % of total area	2017	As % of total area	Change	% change
Gadaref State						
Grassland	2,340.8	42.9	984.0	18.1	-1,356.8	-58.0
Shrubland	137.7	2.5	102.7	1.9	-35.0	-25.4
Forest	807.7	14.8	498.7	9.1	-309.0	-38.3
Total rangelands area	**3,286.20**	**60.3**	**1585.4**	**29.1**	**-1,700.80**	**-51.8**
Agriculture	2,149.4	39.5	3,463.3	63.5	1,313.9	61.1
Settlements	12.4	0.2	40.3	0.7	27.9	225.0
Waterbodies	0.0	0.0	106.5	2.0	106.5	0.0
Bare areas	5.0	0.1	257.5	4.7	252.5	505.0
Total	**5,453.0**	**100.0**	**5,453.0**	**100.0**	**0.0**	
North Kordofan State						
Grassland	3,918.1	21.3	3,953.1	21.5	-35.0	-0.9
Shrubland	4,884.6	26.6	3,457.0	18.8	-1,427.6	-29.2
Forest	646.7	3.5	1,742.7	9.5	-1,096.0	-169.5
Total rangelands area	**9,449.40**	**51.5**	**9,152.80**	**49.9**	**-296.60**	**-3.1**
Agriculture	2,995.1	16.3	3,192.1	17.4	197.0	6.6
Settlements	29.9	0.2	75.6	0.4	45.7	152.8
Waterbodies	1.1	0.1	370.0	2.0	368.9	335.4
Bare areas	5,883.0	32.0	5,568.0	30.4	-315.0	-5.4
Total	**18,358.5**	**100.0**	**18,358.5**	**100.0**		

Changes in biomass production and livestock feed balance situation

In Gadaref State, biomass yield increased by 21% in 2017 in relation to that of 1990, yet reduction in total biomass production was up to -49%. That was due to that grassland area has been decreased by 58% (Table 3). In North Kordofan State, although rangeland areas changed by 16%, biomass production increased by more than 25%, as a result of increased biomass yield by 50% (Table 3).

Feed balance analysis indicated that Gadaref and North Kordofan States are in negative feed balance situation (Table 4). However, the situation is worser in North Kordofan where the estimated carrying capacity in 2017 reflected an overstocking by about 2.4 folds of the actual carrying capacity (Table 4). Abdelkreim and Fadlalla (2013) stated that forage biomass production and carrying capacity (ha/TLU/year) may vary from year to year in the same area as a result of rainfall variation (Figure 1). They ascribed the higher percentage of bare land in open range to overgrazing, agriculture practices and settlements. In our study, there was an observed increase in agricultural land and settlement areas and a decrease in rangeland area from 1990 to 2017 (Table 4). In addition to overall vegetation change and decline, there is also a decline of some key species like perennial *Andropogon gayanus* or some species which have become endangered such as *Belephairs spp.* Species such *Sporoblus pungens* (Difra) and *Syperusspp*. (Sedges) with high nutritive value disappear from the range while less value species such *Orobanche ramosa* (Broomrape) and *Tribulus terrestris* (Puncture vine) dominated (WB, 2021). Boone et al. (2018) project that reducing levels of primary plant production across African rangelands would result in reduced livestock production, productivity, and profitability.

Table 3: Biomass assessment in Gadaref and North Kordofan States between 2000 and 2017

	2000	2017	% change
Gadaref State:			
Biomass yield (kg/ha)	420	510	21
Rangeland area (ha)	2,340,800	984,000	-58
Biomass estimation (ton)	983,136	501,840	-49
North Kordofan State:			
Biomass yield (kg/ha)	209	313	50
Rangeland area (ha)	8,802,681	7,410,087	-16
Biomass estimation (ton)	1,839,760	2,319,357	26

Table 4: Rangeland areas (ha), estimated total biomass production (ton) from different feed sources, feed balance situation and carrying capacity (ha/TLU/year) at Gadaref and North Kordofan States, Sudan in 2017.

Item	Gadaref State	North Kordofan State
Grazing area (ha)*	5,048,900	12,344,900
Grasses biomass (ton)**	779,661	1,267,982
Grasses productivity (ton/ha)	0.154	0.103
Browse biomass (ton)***	282,967	578,327
Crop residues (ton)****	3,799,094	1,232,200
Total biomass (ton)	**4,851,722**	**3,078,509**
Total TLU#	1,750,930.0	2,719,348.1
##Total feed requirements (ton)	4,727,511.0	7,342,240.3
Total feed available (ton)	4,851,722	3,078,509
Feed balance	134.211	(4,263,732)
% surplus/deficit	2.8	-138.5
Grazing area (km^2)	50,489	123,449
Stocking density	34.7	22.0
Current carrying capacity (ha/TLU/year)	2.8097	10.8271
Potential carrying capacity (ha/TLU/Year)	**2.8**	**4.54**

Sources: Extracted from Ministry of Animal Resources, Fisheries and Rangelands (MARF) and Ministry of Agriculture Records (2017)

***Grazing area refers to grass areas, trees/shrubs areas and crop areas; **Grass biomass refers to all grasses/herbs that grow in the grassland and between crops in cropland and those between trees and shrubs in trees/shrubs areas; ***Browse biomass includes all tree fodder, whether it is in trees/shrubs areas, grassland, or cropland; ****Crop residues include residues on cropland.

#One TLU (Tropical Livestock Unit) = 1.0 Camels, 0.75 cow, 0.20 sheep, or 0.15 goat (Rothman-Ostrow et al., 2020).

##Feed requirements of one TLU = 7.5 kg DM per day, = 225.0 kg per month, = 2.7 ton per year

Potential impact of climate change on Sudan Desert sheep future distribution:

Livestock breeds raised on extensive rangeland conditions are exposed to climate change effects (Gowane et al., 2017). For livestock raised in extensive conditions in Sudan over a long period of time, there is a general tendency to acquire characteristics that enable them to adapt to the local environmental and climatic conditions and meet the needs of the people that keep them (Abied et al., 2021). This is generally true if the climate conditions change slowly. However, when the conditions change rapidly, the adaptive link between a livestock population and its local production environment may be broken. The consequences are the extinction or the migration of livestock from the original production environment zones to new zones. The Sudan Desert sheep is a transboundary breed, present in more than one country in Africa (Abied et al., 2021). The current area suitable for this breed is almost the entire Sudan. In year 2050, in the “optimistic” scenario (RCP 2.6) the suitable area (dark green) for the breed would be a large part of the country and the coastal zone (Figure 3 A and C). If the scenario changed and it became rather “pessimistic” (RCP 8.5), the suitable area would be reduced (Figure 3 D), to marginal central-western areas of the country and the coastal zone (Figure 3 B). In year 2070, in the optimistic scenario (RCP 2.6) the situation would not diverge substantially from the year 2050. This would no longer be true if the scenario became rather pessimistic (RCP 8.5). In this case, the reduction of suitable areas for the breed would accelerate due to extreme climate conditions and only small areas (dark green) in the south and along the coast would be available for this breed (Figure 4 F). Reduced rainfall and its high variability (Figure 1) negatively impacted available grazing lands (Table 2) with the consequences of increasing future risks to livestock mortality (USaid, 2016).

CONCLUSIONS

Gadaref and North Kordofan States in Sudan are most vulnerable to climate variability and change. Reduced rainfall has negatively impacted available grazing lands with consequences of increasing future risks to Desert sheep distribution. Correct management of livestock can play an in important role in both mitigation and adaptation (Khalifa and El-Sysy, 2017). Good animal husbandry practices such as improving the genetic potential and resilience to climate change could increase animal productivity (Forabosco and Negrini, 2019). Establishing Desert sheep farmers associations and livestock insurance would further strengthen sheep farmers capacities and resilience to adapt to future risks of climate change.

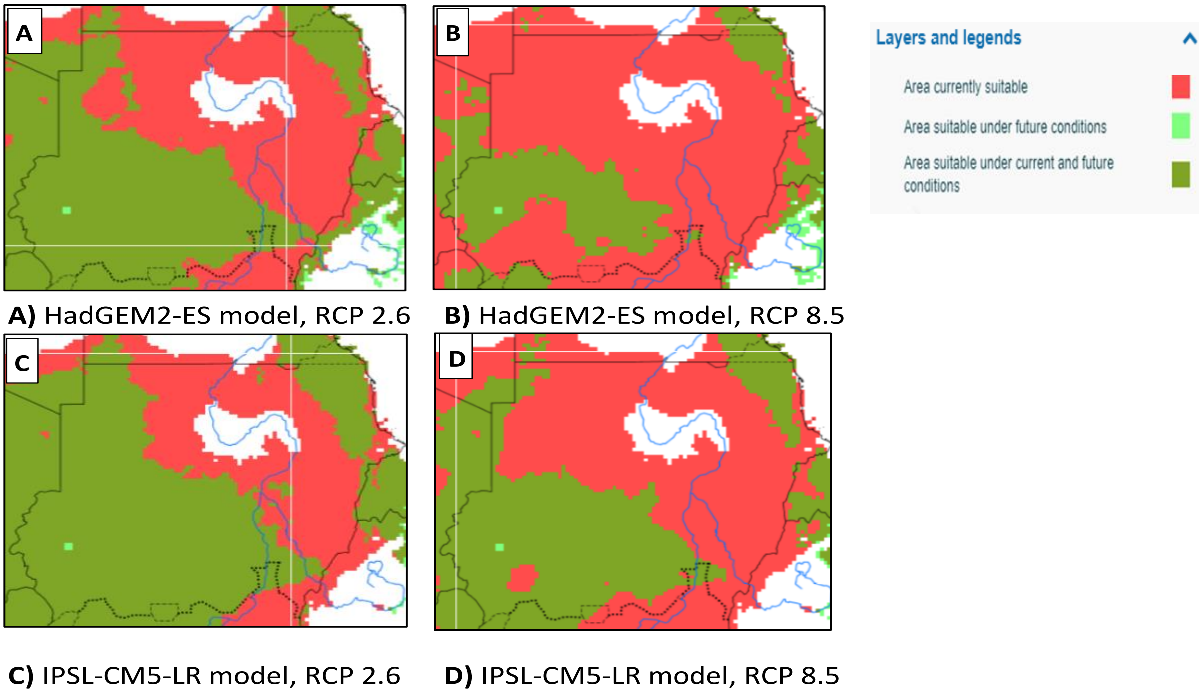

Figure 3: Distribution of Sudan Desert sheep in year 2050

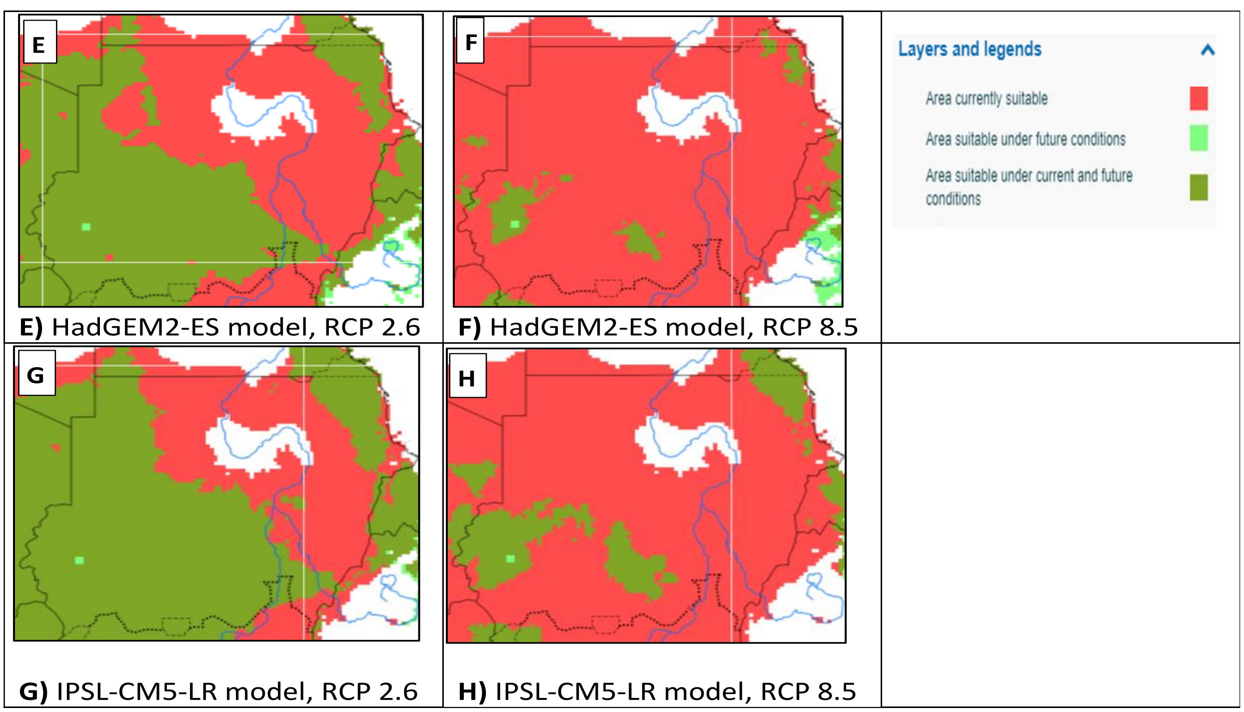

Figure 4: Distribution of Sudan Desert sheep in year 2070

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Authors' Contributions

AM vegetation data measurements and tabulation, AIM climate analyses graphical preparation and preparation of first draft, IF-EM temperature analysis, YK supervision, MT supervision and draft correction, AAK rangeland vegetation and land use analysis, IAA-B Data compilation and analysis, RAH project administration, NGE coordination, SAZ vulnerability analysis, FIA vegetation data measurements and tabulation, FF breed distribution model analysis and writing, AI land use data and analysis, AKO Land use analysis, FME design, data analysis and wrote the first draft. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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