Addressing the gap in protected area design and connectivity in Liberia

Thesis submitted to the Faculty of Geo-Information Science and Earth
Observation of the University of Twente in partial fulfilment of the requirements
for the degree of Master of Science in Geo-Information Science and Earth
Observation.

Department of Natural Resources

Anthony Tony Watson

August 27, 2021

SUPERVISORS

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THESIS ASSESSMENT BOARD

Chairman: Dr. Thomas A. Groen (NRS)

External examiner: Dr Geoffrey H. Griffiths

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ABSTRACT

Protected areas and biological corridors have been proposed as the main methods of conservation to prevent biodiversity degradation and habitat loss, with a particular effort to help reduce climate change globally. Liberia establishes its protected areas to protect its biodiversity, with the majority situated in the northwestern and southeastern parts of the country. However, there is no detail on how much protected areas network covers species habitat in the country. Therefore, this research aims to test the representation of species suitable habitat in Liberia's protected areas, using the spatial distribution of two umbrella species *Loxodonta cyclotis* and *Choeropsis liberiensis,* because of their habitat preference and territory need to sustain a viable population.

The niche modeling algorithm maximum entropy modeling (Maxent) was used to model *Loxodonta cyclotis* and *Choeropsis liberiensis* distribution in the country. This was done using secondary presence-only data downloaded from the GBIF database for both species and ten (10) environmental variables relevant to the species ecological preference collected from various sources. The issues of spatial auto-correlated observations were considered by spatially rarefying species presence points, using 250m as the distance between observations. Additionally, collinearity between environmental variables were evaluated using a set threshold of ($\geq \pm 0.6$) as an elimination requirement for inter-correlated variables.

From the analysis, the model predicted both species suitable habitat locations in the northwestern and southeastern parts of the country at an AUC $\geq$ 0.8. The variables that influenced the model are Euclidean distance to built-up, cropland, roads, and swamp. There is a gap in the protected status of species suitable habitat as they are insufficiently represented in protected areas in the country. Of the suitable habitat with protection status, only the Sapo and Grebo protected area can sustain viable population of *Loxodonta cyclotis*, compare to the *Choeropsis liberiensis* which is sufficient. Fifteen (15) optimum locations were identified to establish a corridor between protected areas. Therefore, the research uncovered a gap in the protection of these species suitable habitat, which could affect other species existence as they umbrella their habitat. `

Keywords: Liberia, Biodiversity, Protected area, Umbrella species, Species suitable habitat, Protection status, Gap, Viable population, Optimum location, *Loxodonta cyclotis*, *Choeropsis liberiensis*, Spatial auto-correlation, Collinearity.

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To begin with, I want to extend my thanks and appreciation to the Living God (the Creator of Heaven and Earth) through his son Jesus Christ, who, by his grace and mercy, I'm here today. From my genesis, he has been my navigation and will continue to be till the end. As it is written, "A man's heart plans his ways, but the Lord establishes his steps" (Proverb 16:9). This is for which I'm highly grateful.

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1. INTRODUCTION

1.1 Biodiversity conservation and protected areas

Protected areas and biological corridors have been proposed as the main methods of conservation to prevent biodiversity degradation and habitat loss, with a particular effort to help reduce climate change globally (Heller & Zavaleta, 2009). Protected areas have further been the main pillars of biodiversity conservation and habitat protection of endangered species (Doran *et al.,* 2010). This is caused by the growing demand for natural products, which has led to habitat loss and degradation of the forest through the collective work of governments, international organizations, local communities (Watson *et al.,* 2014). Human activities have triggered the extinction of 5-20% of biodiversity in many ecosystems globally, and it is estimated that the rate of biodiversity loss is higher than in previous decades (Li *et al.,* 2018). The world's biodiversity was projected to fall from approximately 70% in 2000 to approximately 63% by 2050 (Slingenberg *et al.,* 2009). Main fundamental factors include, but are not limited to, human-induced ecosystem disruption in many complex forms across multiple physical and temporal scales (Slingenberg *et al.,* 2009). According to the Global Living Planet Index, monitored biodiversity population, specifically vertebrate species, have reduced on average to 68% from 1970 to 2016 (WWF, 2020). Therefore, a protected area is essential for conserving biodiversity.

Today, most countries have dedicated themselves to protecting a vast majority of their local biodiversity through protected areas establishment. This biodiversity consists of diverse ecosystems and ecological diversity between species within ecosystems (Possingham *et al.,* 2000). However, the fact that protected areas play a significant role in reducing biodiversity degradation and habitat loss of endangered species, the designing of such protected areas has its limitations and shortcomings. According to Joppa and Pfaff (2009), the design of protected area in most countries and regions have been chiefly hindered by biased toward the location of lower economic worth or inadequate development possibility and data availability. Hence, this can lead to a gap in protected areas networks, causing endangered species habitat loss and degradation outside protected areas. The extent to which protected areas achieve their biodiversity protection aims significantly depends on how well they achieve two objectives. (Margules & Pressey, 2000). Firstly, representativeness, the protected area's ability to represent or sample various important biodiversity over a more extended period. Secondly is persistence; the established protected area should account for the long-term survival of its species and other biodiversity that they host through natural processes and viable populations maintenance (Margules & Pressey, 2000). Here, biodiversity refers to the varieties of life found in one place (WWF, n.d.).

1.2 Biodiversity conservation and protected areas in Liberia

West Africa Guinea forest is a biodiversity hotspot (Mittermeier *et al.,* 1998) and is amongst the world's most fragmented (Mittermeier *et al.*, 2005). The forest is home to many biodiversity and falls within the wealthiest 5% of land area for threatened species such as amphibians, birds, and mammals in the world (Tweh *et al.,* 2015). Moreover, its natural ecosystems have high biodiversity and are the habitat to an unknown number of species that fall within the richest of threatened amphibians, birds, and mammals in the region (Jenkins *et al.,* 2013). However, due to shifting cultivation, rubber plantation, timber extraction, and bushmeat hunting by local communities close to the forest, there is a threat to this vibrant ecosystem that is experiencing rapid degradation (FDA, 2019). Thus, resulting in the need for forest protection by the government of Liberia.

Here protected area is referred to "Any area set aside under Chapter 9 of the Forestry Development Authority Law as a National Forest, Nature Reserve, National Park, Strict Nature Reserve, or other special categories for Conservation purposes" (Government of Liberia, 2006). Liberia is officially protecting about 11% of its total forest (Hooda *et al.,* 2018) compared to its neighboring countries (Junker *et al.*, 2015). Further, "Protected areas in Liberia consist of proposed and designated national parks" (Global Forest Watch, n.d.). In 2003, Liberia's government committed to protecting 30% representing l.4 million hectares of its forest ecosystem to reduce the degradation of its biodiversity (Liberia Forestry Development Authority, 2019). A Reserved network of 12 protected areas covering 14% of the country's forest was designated (FDA, 2007). However, these protected areas were not assessed intensively for their spatial coherence due to a lack of data and expertise (Junker *et al.*, 2015). Tweh *et al.*, (2015) stated in their study that Liberia does not have in-depth knowledge or data on its wildlife diversity.

The World Bank Group report further confirmed an absence of adequate biological informational indexes for Liberia, outside of existing and proposed protected areas, mainly flora species, which are needed for conservation needs (World Bank, 2015). Hence, this could, therefore, result in a gap in the established protected areas. Tweh *et al.,* (2015) further uncovered that chimpanzees and other diverse animal species habitats occur outside of the protected area. Research done by Freeman *et al.*, (2019) reveal that only thirty-nine percent (39%) of suitable habitat for Chimpanzee and elephant species predicted in Liberia fall within the proposed or designated protected areas, the rest was outside of the protected area. Thus, providing the opportunity for their habitat to be encroached on by local communities. According to Liberia's six -national report (2019), wildlife corridors were proposed as a means of connectivity between protected areas. Therefore, identifying the gap in protected areas design and connectivity is essential for informed decision making in Liberia.

1.3 Gap Analysis

Gap analysis seeks to assess the degree to which current protected areas represent biodiversity and recognize elements requiring more protection (Oldfield *et al.,* 2004). Gap analysis strives to spot gaps in species that are not represented in protected or proposed protected areas that maybe included in the formation of new protected areas or existing protected areas (Ahmadi *et al.,* 2020; Davis *et al.,* 1994). Gap analysis ascertains that all ecoregions and locations wealthy in species diversity are covered in conservation management areas by providing information on their gap (Scott *et al.,* 1993). Studies have uncovered that after evaluating the performance of protected areas (PAs) at global scales (Jenkins & Joppa, 2009) and on a regional scale (Ceballos, 2007; D'Amen *et al.,* 2013), biodiversity and their ecosystems are not being protected sufficiently.

Abellán & Sánchez-Fernández (2015) results show that overall, national protected areas and Natura 2000 sites did not adequately represent amphibians and reptile species habitat. Elsewhere, gaps analysis identified under-representation of local species habitat in protected areas of the Indo-Burma Hotspot and thus recommended additional protected areas to increase the representation of species habitat (Tantipisanuh *et al.,* 2016). Because of gap analysis's effectiveness in evaluating protected areas networks, it is essential for effective conservation management (Ahmadi *et al.,* 2020).

Gap analysis overlays species habitat distribution with the layers of existing protected areas and identifies the difference between biodiversity and protection. Habitats that are underrepresented are considered a gap (Scott *et al.,* 1993). Previously, gap analysis methods used vegetation and vertebrate species, birds, and mammals as surrogates for biodiversity mapping (Jennings, 2000). Vegetation served as a determinant for the overall biological diversity because its composition significantly affects species interaction (Franklin, 1993). Because of their role in ecosystem processes (Temple, 1990), mapping their distribution at a useful scale was manageable (Jennings, 2000). To produce a gap map of terrestrial vertebrates, vegetation map and species distribution map (occurrence data) was overlap with the conservation areas as a method for developing species gap (Jennings, 2000). Sritharan & Burgess (2012) overlaid the important birds' habitat layer of Tanzania with existing protected areas to assess the gap in protecting essential birds' area of Tanzania and uncovered an increase in protection by PAs. These analysis methods have been used to spot a gap in protected and expand protected areas domestically and internationally (Vimal *et al.,* 2011). Therefore, similar approaches will be used in this study to spot the gap in PAs in Liberia.

1.4 Suitable habitat and viable population sustenance

Identifying the gap in protected areas is essential, as mentioned previously. Estimating the minimum viable population suitable habitat in protected areas over time is significant to conservation efforts to minimize extinction, especially in developing countries (Gilpin, 1986; Brook *et al.,* 2006). A minimum viable population considers the chances that an actual number of individuals will persist over time in a specific habitat considering stochastic factors (Gilpin, 1986; Nunney & Campbell, 1993). It is estimated that a minimum viable population for a species ranges from 50 to 10,000 individuals in relation to environmental, genetic, and demographical stochasticity (Reed *et al.*,2003). However, it is argued that there are no exact values of the minimum viable population that apply to all populations due to variation in species taxa, thus making this estimate highly uncertain (Flather *et al.,* 2011). Notwithstanding, as there is no analysis done on one of our umbrella species (Pygmy hippopotamus), this estimate will be used as a guide. This also extends to the African forest elephant, taking from the Sukumar & Daniel (1995) analysis on Asian elephants. This guide is used because they both share similar habitats and habitat encroachment (AfESG, 2005).

1.5 Species Distribution Modelling in Gap Analysis

Recent studies have adopted a more advanced approach of gap analysis based on different targets for different conservation features. To determine the gap in the protection of breeding birds in Taiwan, Wu *et al.,* (2013) used hotspot analysis by combining numerous modeling methods, including (Maxent) to build an ensemble model for species, using endemic and endangered species richness as criteria. Further, Spiers *et al.*,(2018) used species distribution modeling (SDM) as a form of gap analysis to predict suitable habitat for Trinidad and Tobago's endemic plant species. This was done using Worldclim2 environmental data and other data sources as a perimeter for modeling to create a map showing endemic richness. Li *et al.,* (2018) combined both SDM (Maxent and Marxan) to designate an area for protection in China as a gap analysis and revealed that species were insufficiently represented in an existing protected area.

A gap analysis requires accurate information on the species occurrence and habitat suitability for an effective gap analysis. Habitat suitability is described as a habitat's potential to sustain a species' ecological needs over time (Kellner *et al.,* 1992). Notwithstanding, such accurate information may not be reliable or accessible in many countries because of a lack of study and insufficient resources (Esselman & Allan, 2011). As such, species distribution modeling is used to predict species presence and habitat suitability in the absence of available data (Rodríguez *et al.,* 2007). Species distribution models (SDMs) are some of the best models for predicting suitable habitats for species over space

(Elith & Leathwick, 2009). They are the best simply because they use spatial and environmental species preference variables with the species presence and/or absence data to model species suitable habitat in the study area (Guillera-Arroita, 2017; Guisan, 2000). Maxent is robust when predicting species distribution because it requires only species presence data and smaller sample size (Esselman & Allan, 2011). Maxent is regarded as the most used SDM (Fourcade *et al.,* 2014) because of its robustness in species prediction (Elith *et al.,* 2011). Notwithstanding, selecting the most suitable SDM technique from a vast set of algorithms for a particular species has risen in popularity. After performance comparison from most studies (Kaky, Nolan, Alatawi, & Gilbert, 2020) there is no uniform consensus for the best model (Norberg *et al.,* 2019). But most studies recommendation referring to model uncertainty accounting during modeling that will affect prediction: choice of variables and sample size (Austin & Niel, 2011;Buisson *et al.,* 2010; Kaky *et al.,* 2020).

SDMs contribute to protected area design and identify critical species habitat (Deka *et al.,* 2017). Freeman *et al.,* (2019) used Maxent to model the distribution of endangered mammal species (Elephant, Chimpanzee, pygmy hippopotamus) and forest connectivity in the upper guinea forest of west Africa. Their research uncovered that 30% of elephants, 30% of chimpanzees, and 19% of pygmy hippopotamuses fall outside protected areas. A similar method was used in this study to predict suitable habitats for the selected species as a gap analysis of protected areas in Liberia. The species relevancy determines the selection of species distribution to use in gap analysis to the protected area goals and data availability for distribution (USGS Gap Analysis Program report, 2013).

1.6 Umbrella Species

Because it is impossible to model the distribution of all species in Liberia, the use of umbrella species approach was used. Umbrella species are species whose protection benefits other co-existing species and their habitat (Seddon & Leech, 2008). A useful umbrella species should have an extensive home range that encompasses diverse habitats that share similar criteria with the target group (Favreau *et al.,* 2006a). In addition to their home range size and habitat suitability, umbrella species are often selected from the list of important species (Possingham *et al.,* 2002), probably because they were covered (Fleishman *et al.,* 2000; Maslo *et al.,* 2016). These species can be a valuable management tool for other species and habitats to benefit from (Maslo *et al.,* 2016). Because by protecting viable population of these species and their habitat will also protect viable population of co-existing species (Thornton *et al.,* 2020). However, this method's potential has been criticized for protecting other essential species (e.g., Lindenmayer et al., 2002; Murphy, Weiland, & Cummins, 2011). Studies have uncovered that umbrella species cannot protect every co-existing species (Roberge & Angelstam, 2004). Although birds and mammals would be represented, other taxa would not be defined because of their limited ecological condition, which does not align with the umbrella species (Roberge & Angelstam, 2004). However, umbrella species are useful for conservation purposes where adequate data are absent (Caro & O'Doherty, 1999).

This is the case for Liberia that does not have detailed biodiversity data, as Tweh *et al.,* (2015) mentioned. Based on the definition of umbrella species, two species were chosen to assess the gap in Protected area design and connectivity. Suitable umbrella species were selected because of their habitat preferences, and territory needed to sustain viable populations. The habitat range of an umbrella species should be broad to be effective to include other species habitats (spatial overlap) and should have the same habitat requirement for other target groups (Niche-overlap) (Favreau *et al.*, 2006b; Suter *et al.,*, 2002; Maslo *et al.,* 2016). As such, this study used the African forest elephant (*Loxodonta cyclotis*; Critically endangered) and pygmy hippopotamus (*Choeropsis liberiensis*; Endangered) as a surrogate for gap analysis from the below list of species being protected in Liberia recorded by the Fifth National Report (Republic of Liberia, 2015). This selection was taken from this list because they are one of the few well-documented species in Liberia (Tweh *et al.,* 2015).

Table 1:List species being protected in Liberia (Republic of Liberia, 2015)

Common Name	**Scientific Name**	**IUCN status** (IUCN Red List, n.d.)	**Habitat Preference (IUCN)** (IUCN Red List, n.d.)	**Home Range (km^2)** (ADW: Home,n.d.)
		PRIMATE		
West African chimpanzee	*Pan troglodytes verus*	Endangered	Savanna or grassland, chaparral forest, rainforest, scrub forest	Range (5-50)
Western black-and white colobus	*Colobus polykomos*	Vulnerable &decreasing	Terrestrial tropical forest, rainforest, scrub forest, moist and dry savanna	Range (0.22)
Sooty mangabey	*Cercocebus atys*	Vulnerable	Tropical terrestrial rainforest, Savanna, swamp, riparian	Range (6-8)
Diana monkey	*Cercopithecus diana*	Endangered & Decreasing	Tropical terrestrial rainforest	Range (0.5-1)
Mona monkey	*Cercopithecus mona*	Near Threaten	Forest, Savanna, Shrubland, Artificial/Terrestrial	Range (0.02-0.2)
Lesser spot-nosed monkey	*Cercopithecus (cephus) petaurista*	Near Threaten	Forest, Savanna, Shrubland, Artificial/Terrestrial	N/A

Olive colobus	*Procolobus verus*	Near Threaten	Tropical terrestrial rainforest	N/A
Campbell's guenon	*Cercopithecus campbelli*	Near Threaten	Forest, Savanna, Shrubland, Artificial/Terrestrial	Range (0.5-5)
Lesser galago	*Galago senegalensis*	Least concern	Forest, Savanna	Average (2.1)
African forest Elephant	*Loxodonta Africana cyclotis*	critically endangered	Forest, Shrubland, Grassland, Wetlands (inland), Artificial/Terrestrial, Artificial/Aquatic	Average (100-2,000)
ARTIODACTYLA				
Jentink's duiker	*Cephalophus jentinki*	Endangered	Forest, Artificial/Terrestrial	N/A
Ogilby's duiker	*Cephalophus ogilbyi*	Vulnerable	Forest	N/A
Yellow-backed duiker	*Cephalophus silvicultor*	Near Threaten	Forest, Savanna, Shrubland, Artificial/Terrestrial	N/A
Zebra duiker	*Cephalophus zebra*	Vulnerable	Forest	N/A
Pygmy hippopotamus	*Choeropsis liberiensis*	Endangered	Forest, Savanna, Wetlands (inland)	Range (1.65-1.85)
Forest buffalo	*Syncerus caffer nanus*	Near Threaten	Forest, Savanna, Shrubland, Grassland, Wetlands (inland)	Range (50-1000)
Bongo	*Tragelaphus eurycerus*	Near Threaten	Forest, Savanna, Artificial/Terrestrial	N/A
Royal antelope	*Neotragus pygmaeus*	Least concern	Forest, Artificial/Terrestrial	N/A
Water chevrotain	*Hyemoschus aquaticus*	Least concern	Forest	N/A
Red river hog	*Potamochoerus porcus*	Least concern	Forest, Artificial/Terrestrial	N/A
Giant forest hog	*Hylochoerus meinertzhageni*	Least concern	Forest	N/A
CARNIVORA				
Leopard	*Panthera pardus*	Vulnerable	Forest, Savanna, Shrubland, Grassland, Rocky areas (eg. inland cliffs, mountain peaks), Desert	Range (13-35)
Liberian mongoose	*Liberiictis kuhni*	Vulnerable	Forest	N/A
African Golden cat	*Caracal aurata*	Vulnerable	Forest	N/A

PHOLIDOTA				
Giant pangolin	*Smutsia gigantean*	Endangered	Forest, Savanna	Range (8.9-10)
Black-bellied Pangolin	*Phataginus tetradactyla*	Vulnerable	Forest, Savanna, Artificial/Terrestrial	N/A
White-bellied Pangolin	*Phataginus tricuspis*	Endangered	Forest, Savanna, Artificial/Terrestrial	N/A
West African Manatee	*Trichechus senegalensis*	Vulnerable	Wetlands (inland), Marine Neritic, Marine Oceanic, Marine Intertidal, Marine	N/A
REPTILES				
Nile crocodile	*Crocodylus niloticus*	Least Concern	Wetlands (inland), Marine Neritic, Marine Intertidal, Marine Coastal/Supratidal, Artificial/Aquatic & Marine	N/A
African slender-snouted crocodile	*Crocodylus cataphractus*	Critically Endangered	Forest, Savanna, Wetlands (inland), Marine Neritic, Marine Coastal/Supratidal	N/A
African dwarf crocodile	*Osteolaemus tetraspis*	Vulnerable	Forest, wetland	N/A
Rock python	*Python sebae*	Not Evaluated	Tropical terrestrial savanna or grassland forest, riparian	Range (0.1-8) (Hart *et al.*, 2015)
Ball python	*Python ragius*	Least Concern	Forest, Savanna, Shrubland, Grassland, Artificial/Terrestrial	N/A
Green sea turtle	*Chelonia mydas*	Endangered	Marine Neritic, Marine Oceanic, Marine Intertidal, Marine Coastal/Supratidal	Range (0.04-6.4)
Loggerhead sea turtle	*Caretta caretta*	Vulnerable	Marine Neritic, Marine Oceanic, Marine Intertidal	N/A
White-breasted guineafowl	*Agelastes meleagrides*	Vulnerable	Forest, Artificial/Terrestrial	N/A

1.6.1 Ecology of Pygmy hippopotamus (Choeropsis liberiensis)

Pygmy hippopotamus preferred habitat is mainly lowland primary and secondary forests close to streams, swamps, and rivers (Robinson, 1970; Bülow, 1988; Eltringham, 1999). Roth *et al.*, (2004) further identified that streams with submerged trees, swamps, and dense vegetation are essential habitat characteristics of the species. As such, this species can contribute to natural ecosystems at a diverse range through its habitat preference for dense vegetation and wetland (Lewison & Carter, 2004). According to Lewison (2011), the pygmy hippopotamus home range for a small group of individuals is approximately 2km^2 for males and about 0.5km^2 for females. This species habitat can also serve as an umbrella for riparian species, as their habitat is considered one of the richest (Andelman *et al.,* 2000). The species habitat has been reduced to forest fragments due to human activities (Schipper *et al.,* 2008). They were listed in 2005 by the IUCN as endangered species (Bogui *et al.,* 2016). The INCN developed the first conservation strategy action plan for the pygmy hippo in Liberia to study their poorly understood population and pinpoint action necessary for long-term conservation goals (Mallon *et al.*,2013 ; Mallon *et al.,* 2011). The pygmy hippopotamus is a native species of the waterways and forests of West Africa, upper Guinea forest (Saragusty *et al.*, 2012).

1.6.2 Ecology of African Elephant (*Loxodonta cyclotis)*

African forest elephant, as listed by the IUCN Red List, is a critically endangered species, according to (Gobush *et al.*, 2021). African forest elephants are broad in their range, and they tend to occupy many habitats, namely, dense forest, open and close savanna, and mountains (Blanc, 2008). Female African elephant home range was identified to be approximately 2000 km^2 using remote sensing telemetry (Blake, 2002; Buij *et al.,* 2007). In an undisturbed forest, elephant home ranges are estimated to be 250 to 400km^2 and 600km^2 in a fragmented forest (Alfred *et al.*, 2012). Their highly fragmented habitat is distributed in seven western African countries, including Liberia (Thouless *et al.,* 2016). Their movement patterns are characterized mainly by human disturbance, permanent water sources, and feeding (Alfred *et al.*, 2012). However, according to Western and Lindsay (1984), water sources in the tropical forest are challenging to attract extensive African elephant migration because water sources in tropical forests are not contributing to their movement (Blanc, 2008; Buij *et al.*, 2007). Therefore, this species was selected because of its diverse habitat preferences and home range size.

Research conceptual diagram

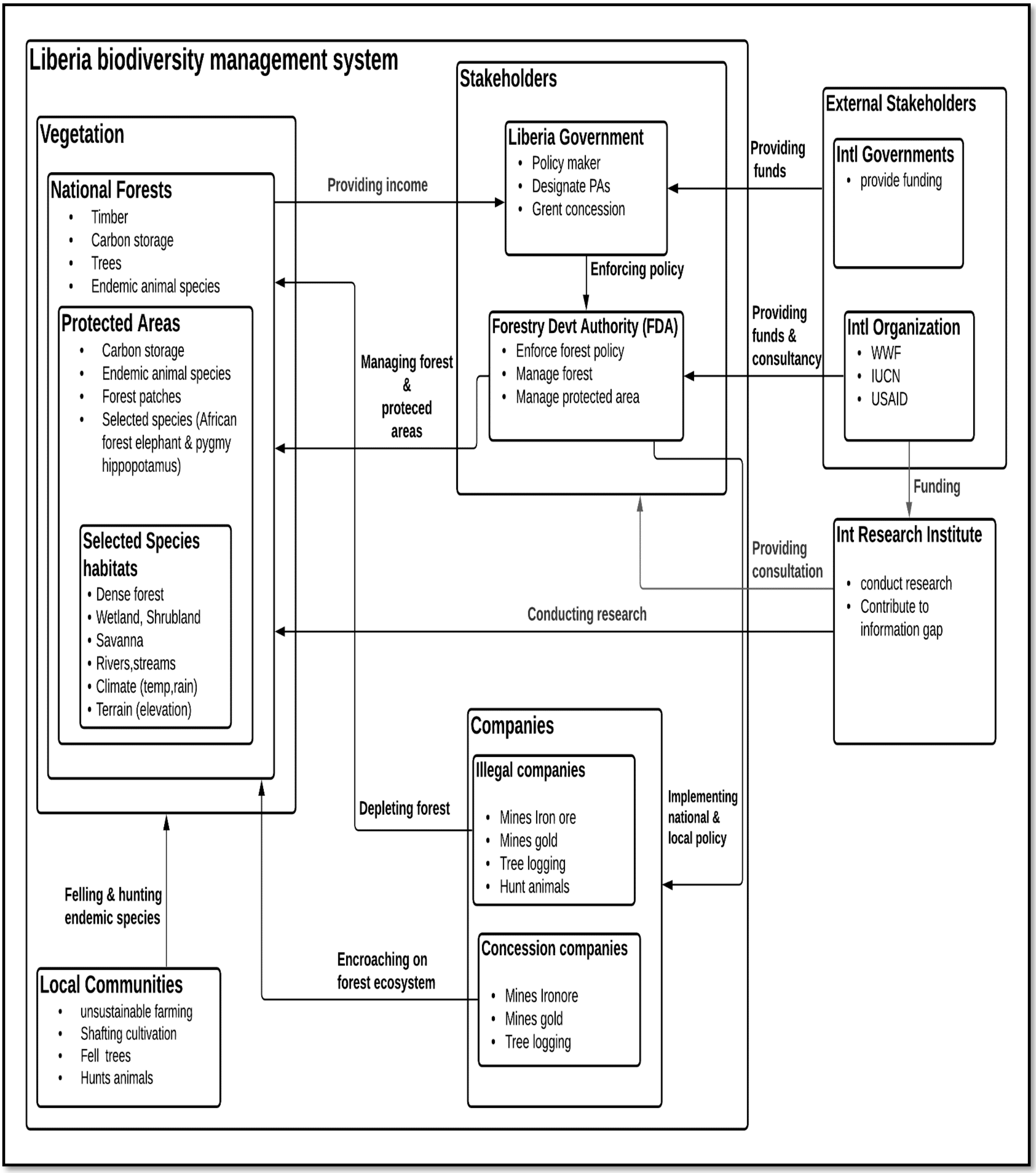


Figure 1:Conceptual Diagram

1.7 Problem Statement

Protected areas have been the main pillars for preventing biodiversity degradation, conserving biodiversity, and habitat protection of endangered species. Liberia designated protected areas to protect its biodiversity. However, these protected areas were not assessed for their spatial coherence due to a lack of data and expertise. As such, there is no detailed information about how well these protected area networks cover species habitats and species that need protection in Liberia. Therefore, this study aims to test the representative of species habitats within Liberia's protected areas using species distribution modeling to inform conservation planning for the betterment of Liberia's rich biodiversity

1.8 Research objective

1.8.1 General objective

This study aims to test the representativeness of species suitable habitat within Liberia's protected areas using spatial distribution of two umbrella species.

1.8.1.1 Specific Objectives and Research Question

- To model the potential distribution of *Loxodonta cyclotis* and *Choeropsis liberiensis* suitable habitat within Liberia
    1. Where are the suitable habitats of *Loxodonta cyclotis* and *Choeropsis liberiensis* in Liberia?
    2. Which environmental variables perform best in predicting the selected species suitable habitat?

- To evaluate the coverage of protected areas for the selected (umbrella) species suitable habitat
    3. How much of the potential distribution and suitable habitat of *Loxodonta cyclotis and Choeropsis liberiensis* is covered by the protected area network?
    4. Are predicted suitable habitat in protected areas of sufficient size to sustain viable populations of the selected species?

- To assess the connectivity of Liberia's protected areas to improve species dispersal
    5. Given Liberia protected areas designation, where are the optimum location for habitat corridors establishment?

2. METHODOLOGY

2.1 The Liberia Context

Liberia is a country located within the tropical rainforest belt on the west coast of Africa (6° 30' N, 9° 30' W) with an estimated area of about 111,369 km² (FDA, 2006). Liberia has a year-round warm and humid climate, mostly along the coast, with two seasons, November to April dry seasons and May to October rainy seasons. The average temperature varies from 24-28 ° C throughout the year and from 65 to 80 percent relative humidity (World Bank Climate Change Knowledge Portal, n.d.). The annual rainfall is more intense in the southern region along the coast, 3,500 to 4,600 mm, and 1,500 to 2,500 mm inland and the Northern region (Schroth*et al.*, 2015). Additionally, the elevation of Liberia ranges from 0 to 1380 m above sea level (asl)., It can be divided into four regions: "coastal plains (100 meters) above sea level, the interior hill (100 to 300 meters asl) , the interior plateau (300 to 600 meters asl) and the mountainous (>600 meters) above sea level" (Republic of Liberia, 2010).

The forest of Liberia (4.33 million ha) lies within the two largest standing continuous forests of West Africa, which encompasses 43% of the upper Guinea forests (Christie *et al.*,2007). Regarding its conservation significance to date, less than 10% of this ecoregion, like others, is being protected (Jenkins *et al.*, 2009). Liberia is host to almost half of this forest, accounting to 43% (Mittermeier *et al.*, 2005). Liberia forest hosts about 2,000 flowering plants, including 225 timber species, approximately 140 mammal species, 615 bird species, 75 known reptiles, and amphibians (Republic Of Liberia, 2017; Tom, 2008). Liberia has 19 marine and terrestrial protected areas (WDPA, n.d.). However, this study is focusing on the forest existing protected areas as a study area. ("East and West Nimba, Foya, Kpo, Gola, Wologizi, Bong, Grebo, Gbi, Sapo, Cestos-Senkwehn, Grand kru-River Gee").

Table 2: Liberia Protected Areas list (FDA, 2017)

Protected Areas	Area in Km^2
Cestos-Senkwehn	832.1
Grebo	971.4
Gola	979.8
Foya	1646.3
Kpo Mountains	837.1
Sapo	1803.6
Grand Kru-River Gee	1351
Gbi	884.1
Bong Mountain	248
East Nimba	135
West Nimba	104.8
Wologizi	1374.3

Research study area

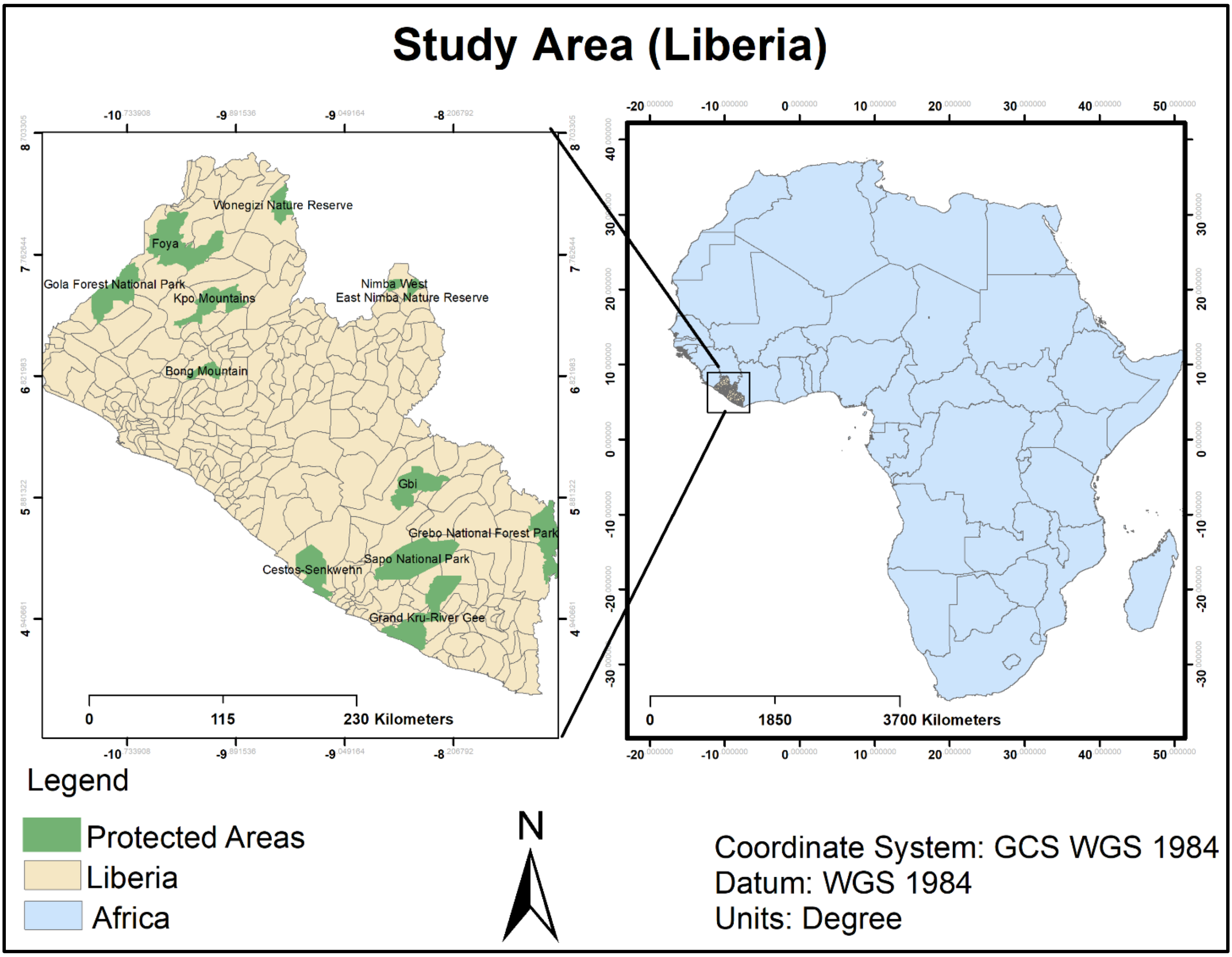


Figure 2: Study Area (Liberia)

Research methodology flow chart

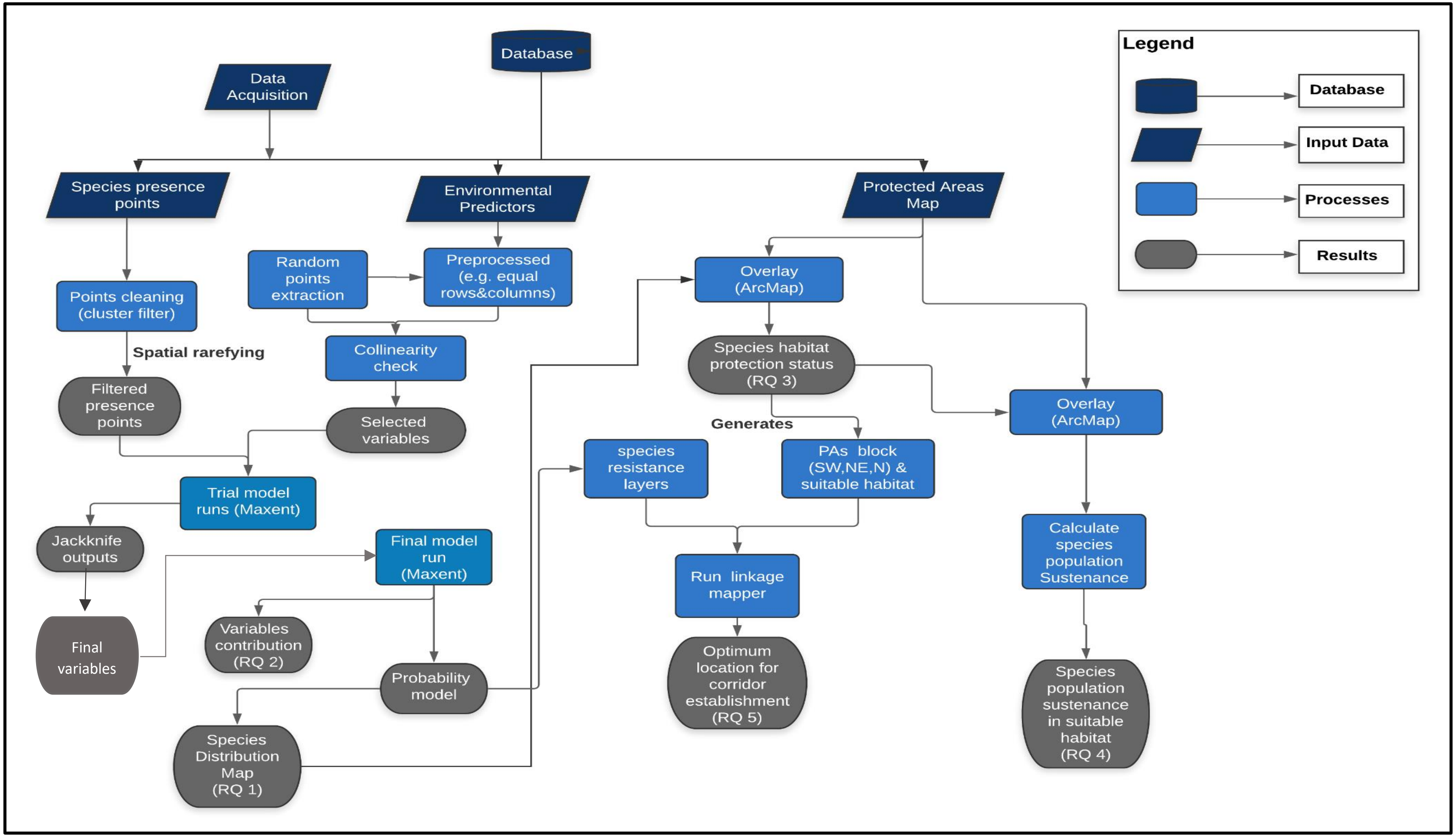


Figure 3:Methodology Flowchart

2.2 Data compilation and pre-processing

This section focuses on the process used to collect data for further analysis in the study. These data are valuable in modeling the selected umbrella species distribution for this study: species presence (only) data, topography data, bioclimatic data, and land cover. These data are essential environmental variables used to predict species distribution (J. Franklin & Miller, 2010)(J. Franklin & Miller, 2010)(J. Franklin & Miller, 2010). The general resolution for variables used in this study is 250m by 250m. This resolution was chosen because the study wants to accurately represent the species habitat's environmental condition (Soberón, 2007;Manzoor *et al.*, 2018). To obtain a uniform dataset, all variables were projected to WGS 84, zone 29. After data extraction and preparation, ten (10) environmental variables were used during analysis. This is because they reflect these species' habitat preferences, which explain their distribution in Liberia (Robinson, 1970; Bülow, 1988; Eltringham 1999; Blanc, 2008;Alfred *et al.*, 2012).

2.2.1 Species Presence Data

Species presence (only) data of the selected umbrella species: African Forest elephant (*Loxodonta cyclotis*), and pygmy hippopotamus (*Choeropsis liberiensis*) were downloaded from the Global Biodiversity Information Facility (www.gbif.org). The points of (428) observations were collected from (2000-2016) and (277) Pygmy hippopotamus from (2011-2016) during the development of the National Action plan for both species in Liberia. These data were collected through a survey (sighting) using handheld GPS to pinpoint location and interviews across the country. Because the species presence point is essential to the modeling process, points accuracy to improves modeled prediction accuracy was considered (Hijimans *et al.*, 2012). This was done by removing spatially auto-correlated presence points as these observations collection are prone to sampling bias (Veloz, 2009). This process was done using spatially rarefy occurrence data SDMtoolsbox (Brown, 2014). This tool filters spatially cluster points at a specified Euclidian distance. During species presence point filtering, 250 meters was used as the distance between points for both pygmy hippopotamus and African forest elephant to align with the grid cell of the environmental variables (Guisan & Thuiller, 2005;Veloz, 2009). This method leaves a single presence point within each ($250m^2$) grid cell of all environmental layers, providing a means for better model prediction accuracy.

Table 3:Species Present points spatial rarefication table

Species name	***Before filtering***	***After filtering***
African Forest Elephant	428	131
Pygmy Hippopotamus	277	177

2.2.2 Topography data

DEM was used to extract the altitude variable, which is essential for the species distribution modeling. Shuttle Radar Topography Mission (SRTM)) 250 meters resolution Digital Elevation Model (DEM) Version 4.1 data was downloaded from CGIAR Consortium for Spatial Information (CGIAR-CSI) (www.srtm.csi.cgiar.org/srtmdata/). This DEM data was used because no-data void in the original data over: rivers, lakes, and mountainous regions is filled through interpolation technique (Reuter *et al.*, 2007). The original data was downloaded at a resolution of 250m from CGIAR Consortium for Spatial Information (CGIAR-CSI) (Jarvis *et al.*, 2008). The data is already processed; however, before masking the image to Liberia's extent, the model was projected to the default coordinate system in ArcMap 10.8.1. After, the altitude variables were extracted for further analysis.

2.2.3 Climatic data

Climatic variables such as annual precipitation and mean annual temperature were derived from the WorldClim database (www.worldclim.org) in an ESRI grid format with a spatial resolution of 1km by 1km (Hijmans *et al.*,2005). Bioclimatic variables are interpolated climatic variables from precipitation, temperature minimum, and maximum from various weather stations worldwide. This thus makes these variables useful for species distribution modeling. To prepare for modeling, the data was projected to the reference coordinate system and masked to Liberia extent. Further, the bilinear interpolation resampling technique was used to resample layers to 250m by 250m as the default modeling resolution; bilinear interpolation because it is a continuous data (Phillips *et al.*, 2006).

2.2.4 Land cover information

Two land cover datasets were used for analysis in this study. The first one is the Africa land cover map, a high-resolution prototype map produced by the European Space Agency (ESA) climate change institute land cover team (http://esa-land cover-cci.org/). The map was produced in 2016 based on a year of Sentinel 2A observations. The land cover has ten (10) classes with a resolution of 20m produced as a prototype to generate feedback for further improvement for future production of high-resolution Africa land cover maps. The second land cover map used in the study is a map produced in 2016 from the Liberia Forest mapping project (Metra & GeoVille, 2016). This map was produced to evaluate the country's forest infrastructure and account for future monitoring, reporting, and verification (MRV) in REDD+ monitoring. The map has a spatial resolution of 1km with an overall accuracy of 90% encompassing ten (10) land cover classes (Metra & GeoVille, 2016). The map was produced using RapidEye data collected between (Dec 2011 and Feb 2013) and Landsat 8 (Dec 2013 and early 2014). To conduct analysis, both maps were downloaded in GeoTiff format. Out of these land cover maps, Euclidean distance to land cover classes that are important for species habitat prediction were extracted. Euclidean distances to these land cover classes are used instead of categorical data because these species are highly mobile. Therefore, to account for limitation to their dispersal ability, distance to these land cover classes was considered as they provide detailed information relating to the species' needs or avoidance of a specific habitat. Factors limiting species dispersal can strongly influence their habitat suitability distribution (Maharjan *et al.*, 2017).

Table 4: Land cover data

NO.	AFRICA (ESA)	LIBERIA (Metra & GeoVille)
1	Tree cover areas	Forest >80%
2	Shrub covers areas	Forest 30 – 80%
3	Grassland	Forest <30%
4	Cropland	Mangrove & Swamp
5	Vegetation aquatic / regularly flooded	Settlement
6	Lichen Mosses/ sparse vegetation	Surface water bodies
7	Bare areas	Grassland
8	Built up area	Shrub
9	Snow and/or ice	Bare soil
10	Open water	Rock & Sand

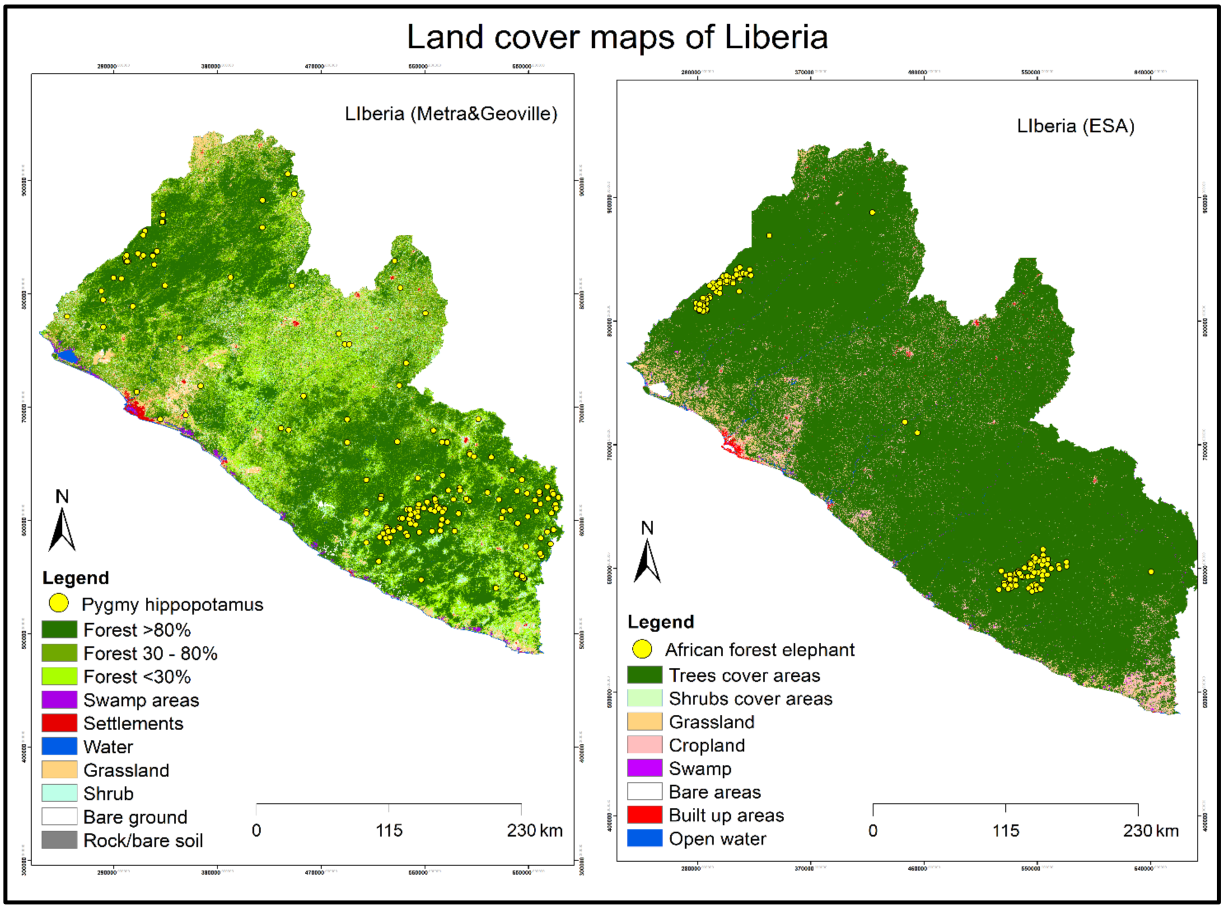


Figure 4: Land cover maps of Liberia

2.2.5 Linear data variables: roads and waters

The information related to roads and waters was taken from the open street map (OSM) inline database (download.geofabrik.de/africa/liberia.html). The data ware downloaded in an ESRI compatible shapefiles format and imported into ArcMap for further analysis. The shapefiles were reprojected to the default projection used for the study WGS 84 UTM Zone 29. Based on the description of species ecology and habitat requirements (sections 1.6.1 & 1.6.2) (Boafo & Sani, 2011; Lanka *et al.*, 2011; Bogui *et al.*, 2016; Poulsen *et al.*, 2018), these variables Euclidean distance were calculated. During distance to roads, rivers, and streams generation, the shapefiles were converted to raster using the feature to raster tools. After (distance to roads, rivers, and streams) were calculated separately using the Euclidean distance tools in the spatial analyst toolbox at a spatial resolution of 250m, as display in Table 5 below.

Table 5:List of Environmental variables considered for modeling

No.	***Environmental layers***	***Description***	***Source***
1	Mean Annual Temperature	Degree Celsius	WorldClim
2	Altitude	Altitude (meters)	SRTM (DEM)
3	Forest>80	Distance to dense forest	Liberia Land cover
4	River	Distance to rivers	Open Street Map
5	Stream	Distance to stream	Open Street Map
6	Swamp	Distance to swamp	Africa Land cover
7	Cropland	Distance to cropland	Africa Land cover
8	Road	Distance to roads	Open Street Map
9	Mean Annual Precipitation	Mm	WorldClim
10	Built-up	Distance to built-up	Africa Land cover

2.3 Environmental layers elimination and multi-collinearity check

Collinearity exists among environmental variables, which can cause model overfitting (Guisan *et al.*, 2002). Therefore, to reduce collinearity, a multi-collinearity check was done to identify variables that affect other variables (high correlation), thus influencing model quality (Guisan *et al.*, 2002;Xu *et al.*, 2019). A random sample of (N=1000) was selected from the country to conduct the collinearity check between environmental layers in Liberia. These random points were used instead of the species presence points used for the species modeling in order to improve the range of information generated from the environmental layers and accuracy (Rademaker *et al.*, 2019).

The random points were extracted from the country using the Sampling Design Tool for ArcMap. This tool provides a means to effectively develop sampling strategies in a geographic information system (GIS) environment developed by the National Oceanic Atmospheric Administration (NOAA) Biogeography Branch (http://ccma.nos.noaa.gov/). In light of eliminating spatial multi-collinearity, a minimum distance between samples points was set to 250m corresponding to the grid cell of the environmental variables (Guisan & Thuiller, 2005; Veloz, 2009). These points were used to extract information from the layers using the extracted value to point tools in ArcMap; the extracted points were used in R studio for collinearity analysis. During the check, the Pearson correlation coefficient (r) was used to test variables' independence from another variable (Díaz-Gómez *et al.*, 2013; Dormann *et al.*, 2013).

The study set a restrictive threshold correlation coefficient of ($\geq \pm 0.6$) as opposed to the commonly used threshold ($\geq \pm 0.7$) to avoid multi-collinearity and to adapt statistical assumption (Syfert *et al.*,2013); therefore, variables correlation value $\geq \pm 0.6$ was eliminated (Dormann *et al.*, 2013). Jackknife test of variables importance was further used after experimental model runs to eliminate variables that had less contribution to the model prediction after the collinearity check. After this, the final variables used for species modeling were selected.

2.4 Species distribution modelling (Maxent)

Many models exist for modeling the potential distribution of species; some of the most widely used are generalized linear models (GLM), generalized additive models (GAM) (Guisan *et al.*, 2002;Hastie *et al.*, 2012), and boosted regression trees (BRT) (De'ath, 2002). In this study, the Maximum Entropy Modeling (Maxent) was used because it is robust and has been reported to give good results with presence-only data available (Esselman & Allan, 2011; Elith *et al.*, 2011). Maxent uses presence-only data and relevant environmental variables of the species to model its distribution (Elith *et al.*, 2011). As a result, each of the environmental variables use in the model should have a suitable feature that aligns with the empirical data of the model (Farashi & Shariati, 2017). Suitable habitat identified by the model is characterized by a probability values ranging from 0 to 1, which results in the generation of curves of environmental variables estimating the linkage between both species suitable habitat and environmental variables (Khanum *et al.*, 2013).

During the Maxent modeling process, species presence-only data was converted to a CSV file format. This is followed by environmental layers projection to the study default coordinate system, same cell size, and equal rows and columns before layers conversion to ASCII file format. Before further analysis, environmental layers were specified as either continuous or categorical where necessary. The Maxent model was run using the defaults settings except for the maximum iterations. Regularization multiplier =1, maximum iteration=1000, convergence threshold =10^{-5}, the maximum number of background points = 10,000 to reduce risk of under or over fitting model relationship (Kumar, 2012;Yang *et al.*, 2013; Wan *et al.*, 2014; Fourcade *et al.*, 2014). The 5-fold cross-validation method was used to produce a series of response curves, including a Jackknife test output for validating the model performance (Pearson *et al.*, 2007). The 5-fold cross-validation method generates five (5) model predictions by excluding one record for testing, and the other (n-1) fold are used for training data in each prediction, out of which an average model is developed from the five model predictions (Stevenson *et al.*, 2014; Ferrari *et al.*, 2018).

To further test for variable importance and elimination, separate experimental models using all environmental variables were run. Individual variables were eliminated one at a time, and a model output was assessed with the remaining variables (Matawa *et al.*, 2012). After this, a final model run was done, producing a logistic probability suitability output map for both species was produced displaying probabilities that ranged between 0 and 1 of species habitat suitability. The predicted probability map was reclassified using the reclass tool in ArcMap to generate the species presence (1) and absence (0) binary map for both species. The predicted binary map for both species was created using the logistic threshold of equal training sensitivity and specificity, Pygmy hippopotamus (0.173) and African forest elephant (0.339), respectively (Cantor *et al.*, 1999). The sensitivity is when the model predicts a known presence, and specificity is when the model predicts a known absence within the study area. This threshold is more robust for reclassifying to suitable and unsuitable niche presence and absence (Liu *et al.*,2005). The model performance was evaluated using the Area Under the Curve (AUC) of the receiver operating characteristic (ROC). The AUC is a measure of the model discriminatory power providing a threshold independently ranging from 0.5 (random) to 1 (perfect discrimination) where a threshold greater than 0.7 excepted as good model performance (Pearson *et al.*, 2007;Rebelo *et al.*, 2010).

2.5 Predicted suitable habitat in Liberia and its protected status

Here the species total suitable habitat estimation was first done for the whole country of Liberia, followed by calculations of the predicted suitable habitat within the protected areas. Both species predicted binary maps as mentioned above were used to identify the gap in protection status of both species' suitable habitat. To begin with, the total suitable habitat for individual species in Liberia was calculated. Suitable habitat areas were summed and multiplied by the raster image's cell sizes (m^2). Afterward, the sum of both species presence and absence was multiplied by the raster image cell size (m^2) divided by the species presence coverage sum to obtain coverage in percent. Additionally, to generate suitable habitat that is covered by protected area, the protected areas layer was clipped with the suitable habitat binary map of Liberia using the extract by mask tool in the spatial analyst toolbox. Based on this clipped raster layers, the total suitable habitat covered by the protected areas was generated in meters (m^2) and percentage using the same procedure mentioned above. For convenient and uniform visualization, final results were converted from m^2 to km^2.

2.6 Protected area suitable habitat capacity to sustain viable species population

The ability of a species to persist in habitat over a longer time depends highly on the capability of that habitat to sustain a viable population to avoid extinction (Brook et al, 2006) . Therefore, based on the known suitable habitat in PAs of both species, the research evaluated the ability of those habitats in each PAs to sustained each species' viable population over time. This is the number of individuals that can survive in suitable habitats per km^2 considering stochastic factors, as previously mentioned (section 1.4). To achieve this, the carrying capacity of both species was estimated based on known population densities and the area of predicted suitable habitat from the species binary map.

This was done by converting the species binary map to an ESRI shapefile using the raster to polygon tools in ArcMap. From the shapefiles of individual protected areas, the suitable habitat (presence) sum was calculated. Based on the computed presence, the carrying capacity of species was predicted using the known population density per km^2 of each species. The known population density on the African forest elephant was derived from studies done in Liberia and Pygmy hippopotamus from a study done in Sierra Leone. Sierra Leone because a study has not been done in Liberia for this animal and Sierra Leone shares and have similar environmental conditions as Liberia. The population density for the African forest elephant was estimated to be $0.2km^2$ (Boafo & Sam, 2011), and the Pygmy hippopotamus population density was 0.8 and 2.5 individuals per km^2 (Roth *et al.*, 2004).

Before calculation, the pygmy hippopotamus population density average was obtained 1.65 individuals per km^2. The following equation was used to derive suitable habitat's carrying capacity (Doko *et al.*, 2011).

$$N = A * PD$$

Where N is the species population, A is area km^2 (suitable habitat) and PD is population density (individuals/km^2).

2.7 Optimum location for corridor establishment in Liberia

Identifying paths for connecting suitable habitat patches and protected areas is one of the most efficient approaches to ensure species survival. (Xun et al., 2014; Zacarias & Loyola, 2018). Amongst others, habitat connectivity achieves an improvement of several ecological processes: genetic flow, migration, and dispersion important to changes in the environment (Zeller et al., 2012). Optimum location for species migrations between protected areas in Liberia were identified, given the current distribution of both selected species.

To this end, the Linkages Mapper toolbox was used as an extension tool in ArcMap to perform the Least Cost Path Analysis (LCP) between suitable habitats and protected areas. The tool employs a theory based on movement between predicted habitats as a function of conductance of the intermediate landscape (McRae et al.,, 2008). For the least cost pathway establishment, the analysis required a resistance layer and a unique sample site ID to connect patches. In this context, the resistance layer consists of variables from the landscape, encompassing cell values associated with the cost (reduction of survival) of species dispersal in the environment (Zeller et al., 2012; Jones, 2015).

Because the study involves the use of two species as an umbrella for other species, therefore, to establish the least cost path (LCP) between protected areas, the resistance layers of both species were used. This was accomplished using created the resistance layer (1 to 100 range) and PAs suitable habitat polygon clipped from the binary map of individual species (Glover-Kapfer, 2015). To create the resistance layer, the maxent probability layers for both species was normalized, ranging from (0 to 100) using the CorridorDesigner toolbox in ArcMap. The normalization assign value in each pixel within a raster grid over the country. From this normalized layer, the resistance layer was generated using the formula below.

(100-normalize layer) +1

This produced a resistance value for each pixel in the layer ranging from (1 to 100) as zero can't be used in the toolbox to perform LCP (Glover-Kapfer, 2015). The resistance surface layer produced an inverse habitat suitability score (low resistance 1 and high resistance 100) map representing characteristics of the landscape, encompassing cell values associated with the cost of species movement (Jones, 2015). From the produced resistance layers, an average resistance layers from both species resistance layers (Marrotte & Bowman, 2017) were calculated using the raster calculator tool in ArcMap.

This average species resistance surfaces layer was generated to ascertain that information from both species resistance layers is represented. This average resistance layer for both species was used to identified optimum location for corridor establishment between protected areas. Furthermore, as a means to connect individual species suitable habitat with protected status (Wade et al., 2015). Individual species resistance layer and suitable habitats were used.

2.8. Ethical Consideration

This research will not consider individuals' involvement in the form of surveys, workshops, and focus group discussions. However, confidentiality and privacy are regarded because of the sensitivity surrounding these species used in the study. Moreover, to make this research successful, secondary data were used and taken from private institutions that require the use of their data in an ethical manner; all of the data required in this research is open for public use. Data used were credited to the organization or sources taken from according to their copyright and data use requirements. This was done in the form of proper references and citations of data providers.

Moreover, the fact that no ideas are new to the scientific world, this research benefits immensely from previous research done on this research topic or similar topics. As such, all research articles used were referenced and cited in the appropriate format as required by the thesis committee of the ITC. Regarding risk consideration, in the event of data limitation and requirement for this research, the only contingency plan for alternative action was the reformation of the thesis research question and methodology.

3.RESULTS

3.1 Multi-collinearity check

Based on the correlation analysis between variables, it was uncovered that some variables were intercorrelated. From the analysis, attitude and annual precipitation were negatively correlated, indicating that the use of both variables during the modeling of individual species distribution will most likely affect the final model output. This correlation was expected as altitude is a proxy for temperature changes, and it is also used in interpolation of climatic variables in WorldClim. The relationships between the distance to built-up and the distance to cropland are positive, indicating that as the distance to built-up reduces, the chance of finding cropland increases. This makes sense because the majority of the country's croplands are closer to built-up. The correlation relationships between Distance to Swamps, rivers, and streams are positively associated, indicating that the presence of rivers represents the proximity of stream and swamp. However, these variables were retained as their correlation values were low, including all other variables with lower correlation values, except Annual precipitation, as displayed in Table 6 below.

Table 6:Correlation matrix between environmental variables

	Builtup_D	Crop_D	River_D	Alt	Annu_P	Mean_T	Roads_D	Stream_D	Swamp_D	Forest_80_D
Builtup_D	1	0.5	0.3	0.2	0.0	-0.1	0.3	0.2	0.5	-0.3
Crop_D	0.5	1	0.2	0.2	0.0	0.0	0.3	0.2	0.2	-0.3
River_D	0.3	0.2	1	0.2	-0.2	-0.2	0.0	0.5	0.4	-0.1
Alt	0.2	0.2	0.2	1	**-0.6**	-0.4	0.1	0.1	0.3	-0.2
Annu_P	0.0	0.0	-0.2	**-0.6**	1	0.1	0.0	-0.2	-0.2	0.0
Mean_T	-0.1	0.0	-0.2	-0.4	0.1	1	0.0	-0.2	-0.1	0.0
Roads_D	0.3	0.3	0.0	0.1	0.0	0.0	1	0.0	0.2	-0.2
Stream_D	0.2	0.2	0.5	0.1	-0.2	-0.2	0.0	1	0.2	-0.2
Swamp_D	0.5	0.2	0.4	0.3	-0.2	-0.1	0.2	0.2	1	-0.2
Forest_80 D	-0.3	-0.3	-0.1	-0.2	0.0	0.0	-0.2	-0.2	-0.2	1

Alt**:* Altitude, ***Annu_P: Annual Precipitation**,** ***Mean_T**: Mean* Annual Temperature, ***Built_D*:** Distance To Built-up, ***Stream_D:*** Distance To Stream, ***Crop_D:*** Distance To Cropland, ***River_D:*** Distance To Rivers, ***Road_D:*** Distance To Roads, ***Swamp_D:*** Distance To Swamp, ***Forest_80_D:*** Distance to Forest

3.2 Final variables screenings for modeling species distribution

Table 7 below are results from variables used to build the final model for species prediction distribution (Pygmy hippopotamus and African forest elephant). During variables screening, the final results from the correlation analysis were used in several experimental model runs; this was done to produced final variables to model both species based on the jackknife. As indicated in the table below, variables eliminated after the collinearity analysis were excluded from the experimental run for further screening in the jackknife model. After separate experimental runs, all variables were retained because all variables were suspected to be important to the final model output. Final environmental variables used for modeling the selected species distribution are specified as (Pygmy and Elephant model).

Table 7: Screening of Environmental variables used for modeling

Name	*Collinearity check*	*Jackknife*	*Pygmy model*	*Elephant model*
Altitude	X	X	X	X
Mean Annual temperature	X	X	X	X
Annual precipitation	X	-	-	-
Builtup_Dis	X	X	X	X
Stream Dis	X	X	X	X
Cropland Dis	X	X	X	X
River Dis	X	X	X	X
Road Dis	X	X	X	X
Swamp_Dis	X	X	X	X
Forest_80_Dis	X	X	X	X

Variable used for modeling (**X**) and variables excluded from modeling **(-)**

3.4 Spatial distribution of selected umbrella species in Liberia

Based on the environmental variables used, the model could predict the study's two selected species distribution within the country with good model accuracies. Each model prediction had an Area Under the Curve (AUC) value of 0.9 (African forest elephant) (Figure 6) and 0.8 (Pygmy hippopotamus) (Figure 7), indicating that each model performed well in discriminating the presence and absence of the two species. From first glance as shown in the figure below, there is little or no suitable habitat in the center of the country for both species especially the African forest elephant.

Most species' suitable habitat distribution predicted by the model is divided into two blocks in the country. These blocks are situated in the northwestern and southeastern, where the protected area's networks are spatially located, and these locations are known to harbor these species. Contrary to Pygmy hippo suitable habitat distribution, African forest elephant suitable habitats are relatively low, especially in the northwestern block, with suitable habitat predominantly situated in the Gola protected area. This indicates that suitable habitat patches of African forest elephants, as identified by the model, are in serious danger.

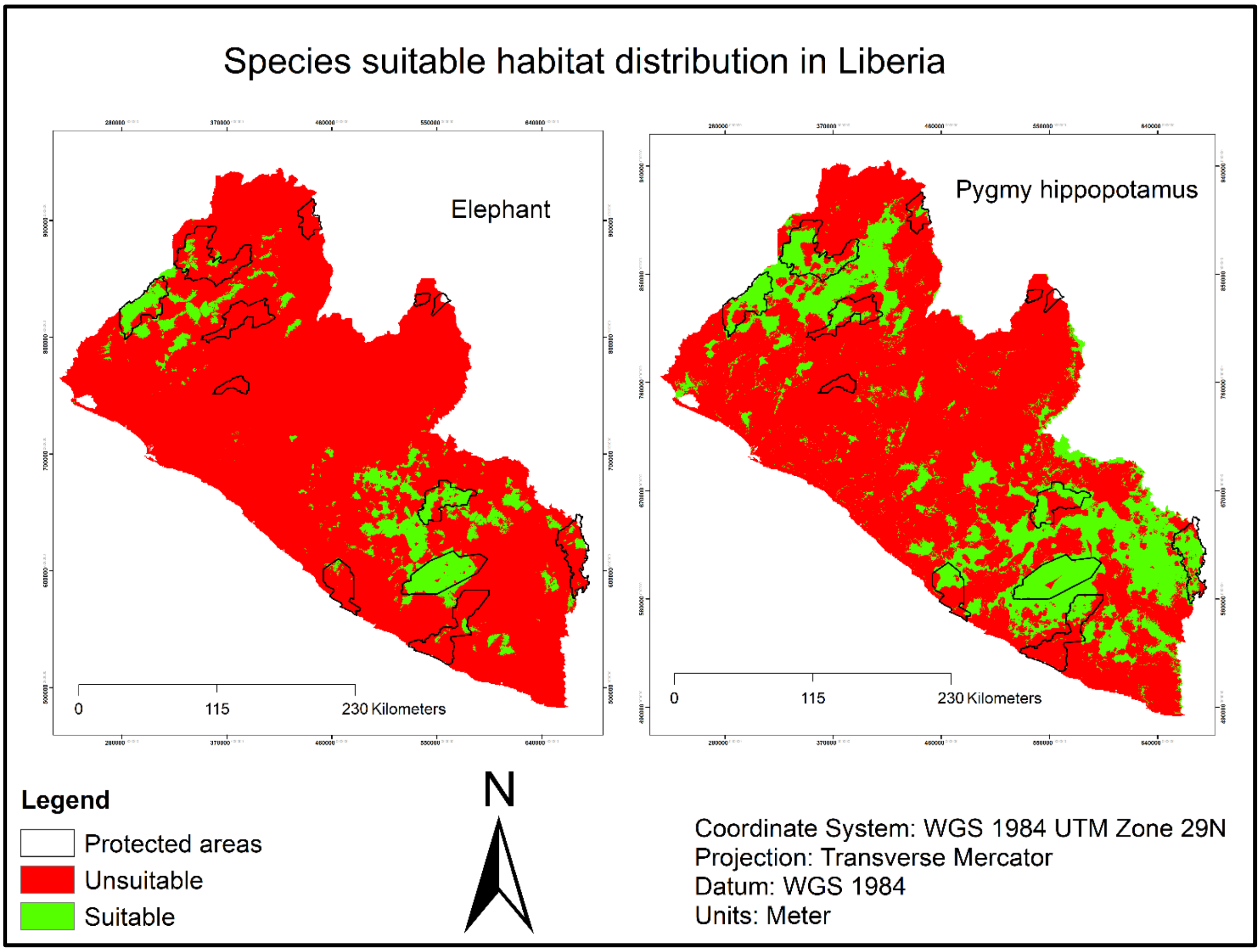
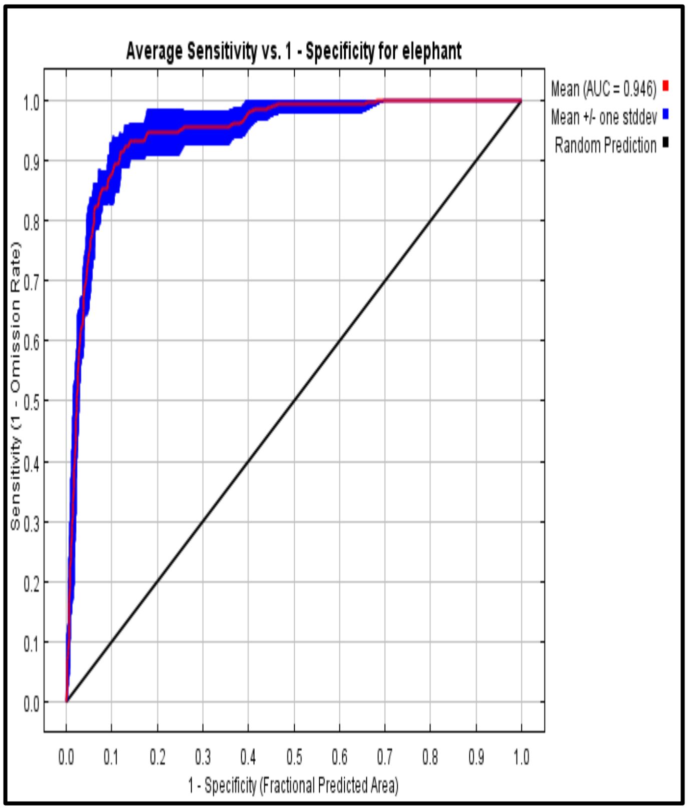


Figure 5: Species suitable habitat distribution in Liberia

ROC Area Under the Curve for both models



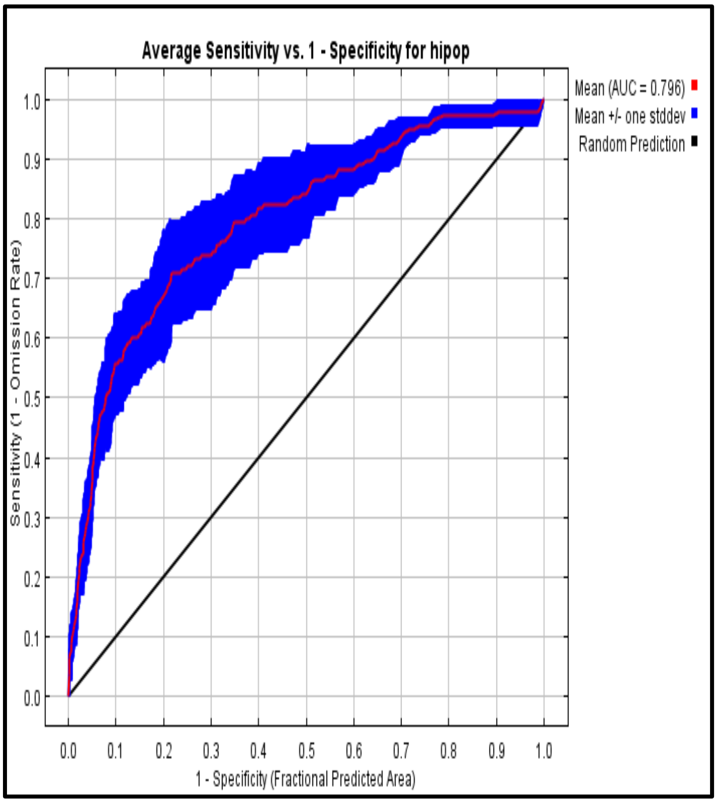


Figure 6: African forest elephant AUC

Figure 7:Pygmy hippopotamus AUC

3.3 Variables performance and contribution to species prediction

(a) Jackknife test of variables importance for both Pygmy hippopotamus and African forest elephant

The jackknife model creates many models from residual variables after individual variables are run in exclusion. After this, a model is created using individual variables in isolation. In the African forest elephant model, variables (distance to built-up, cropland, and roads) further presented higher gain. As mentioned above, these variables mainly (built-up) contained more information when used in isolation than (altitude, distance to forest, and swamp) when building the model. Notwithstanding, the variable (distance to cropland) appears to have more information that is not represented in other variables, therefore when omitted, it will affect the model substantially. Expectedly, as displayed below, the variables (distance to forest) contributed less to the model predictions. This is surprising because the animal habitat is generally associated with forests.

Therefore, to explore the rationale of these findings, a histogram was plotted to show the distribution of samples within (distance to forest) variables and a variable with the highest gain (distance to built-up) as shown in (Figure 9&10). Based on the displayed histogram of (Figure 9), most of the samples from the variable (distance to forest) have a zero value, with distribution skewed to the left. Contrary to (Figure 9), as displayed in (Figure 10), the samples from the variable (distance to built-up) have a bell shape indicating an even distribution of samples. This could hypothetically cause (distance to forest) low contribution to the model as the majority of the sample points are in the forest, with only 5 to 10 observations 200m away from the forest. Further discussion on this reasoning will be addressed in the discussion of this study.

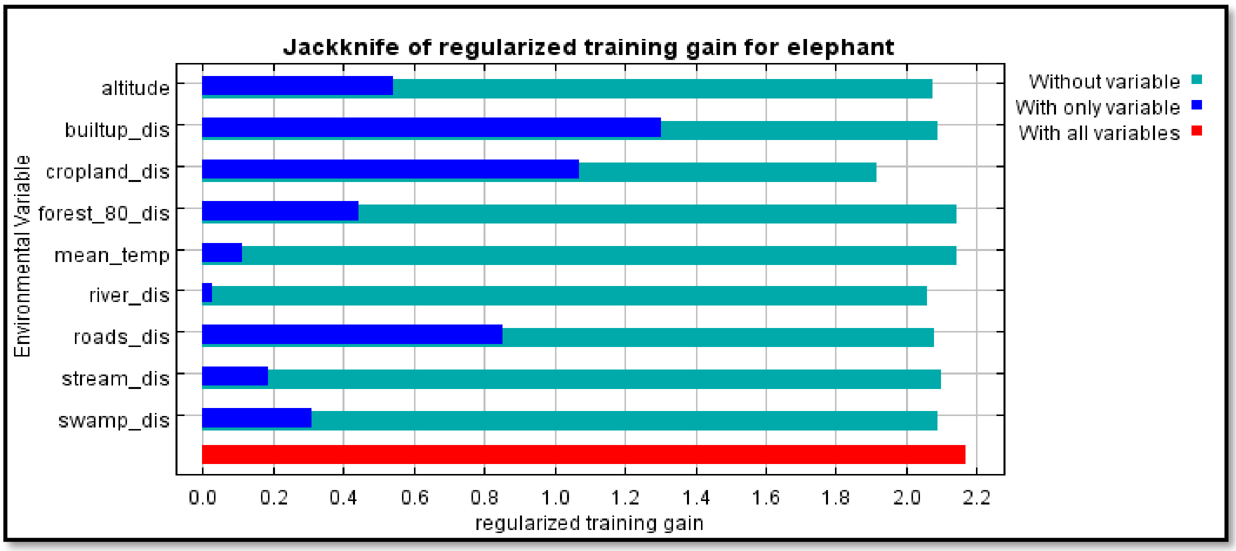


Figure 8:Final African Forest Elephant model Jackknife output

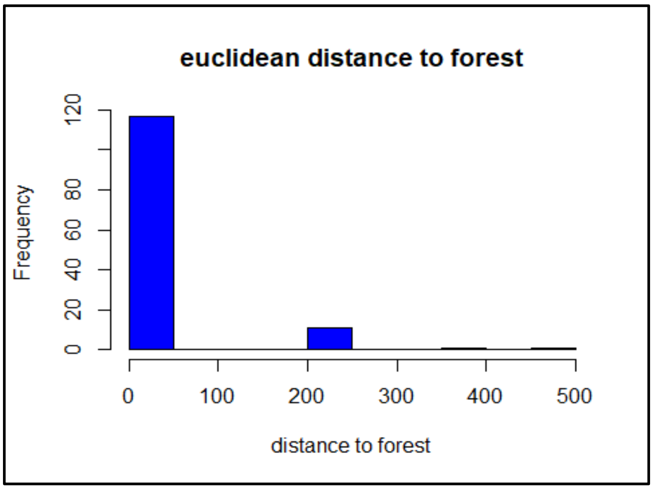


Figure 9:Distance to forest histogram (elephant)

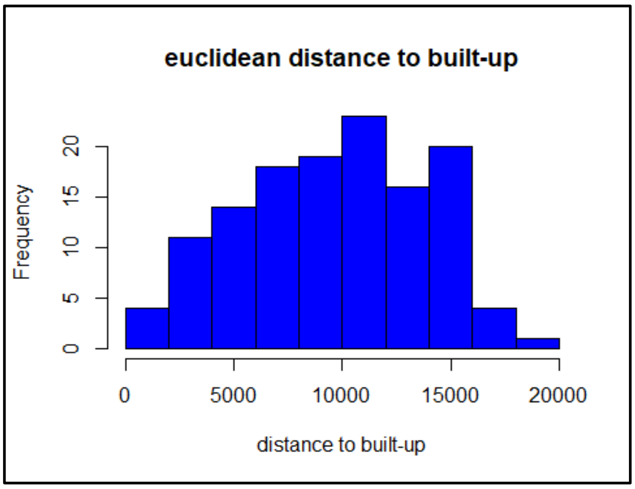


Figure 10:Distance to built-up histogram (elephant)

Figure (11) is a final Jackknife displaying the contribution of each environmental variable used in training the Pygmy hippopotamus model. When used in isolation, the variables with the highest gain are the (distance to built-up, cropland, and swamp) compared to other variables (mean annual temperature, distance to rivers), indicating these variables have useful information when predicting the African forest elephant suitable habitat in isolation. However, of all the variables (distance to built-up) have the highest gain when used alone, including more information that is not present in other variables. Therefore, when omitted from modeling will affect the model prediction significantly. The variables (annual temperature, distance to forest, and rivers) had less contribution than their counterpart. Surprisingly, the variable distance to forest has a low contribution to the model output, as the species habitat is associated with forest. Therefore, as done previously, the species samples within the forest and built-up variable were explored for comparison as it is the highest contributing variable to the model prediction. Based on the forest histogram (figure 12), most of the samples have a value of zero, compared to built-up (figure13), which has sample values that are almost evenly distributed.

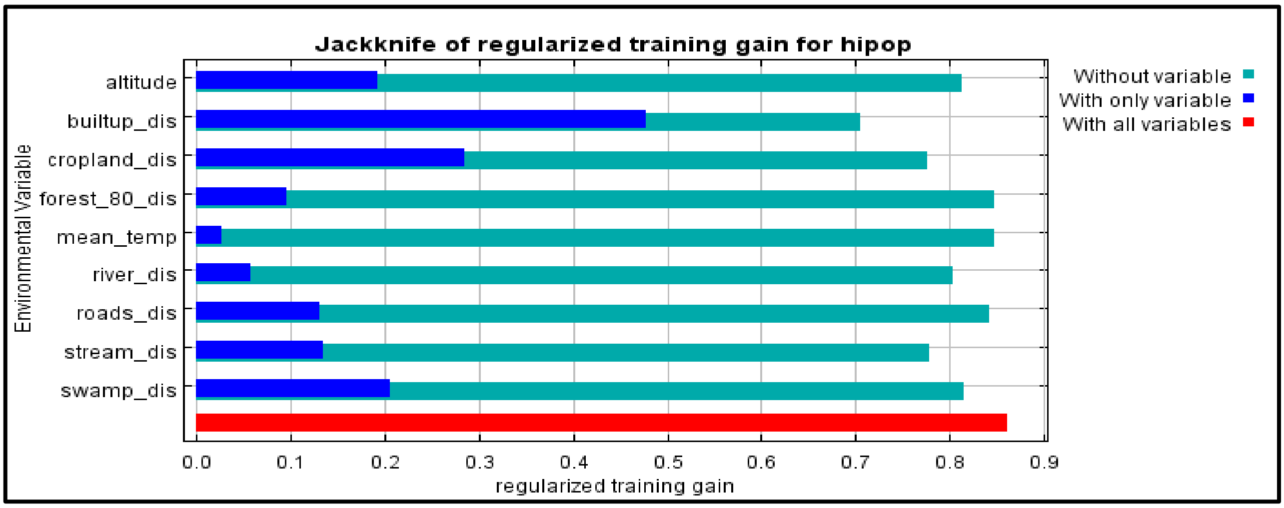


Figure 11: Final Pygmy hippo model Jackknife output

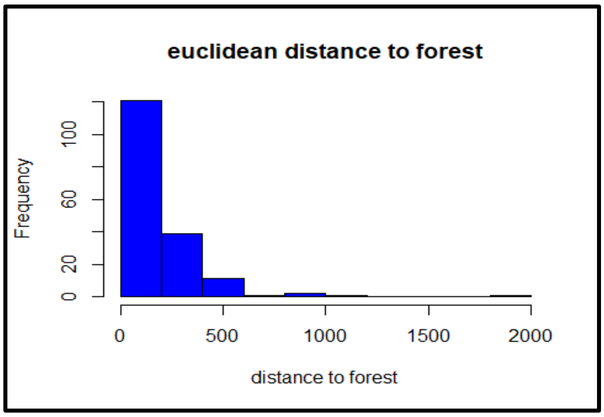


Figure 12: Distance to forest histogram (hippo)

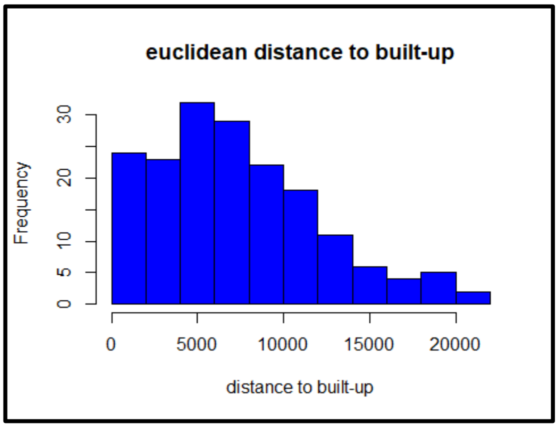


Figure 13: Distance to built-up histogram (hippo)

(b) Environmental variables response curves for the African forest elephant and the Pygmy hippopotamus

The curves shown in (Figures 14&15) represent a maxent model created using only corresponding environmental variables. Based on the response curves from the African forest elephant model (Figure 14). As the distance to the forest increases, the probability of finding the African forest elephant drops from ~0.55 to nearly 0, indicating that the species prefer being closer to dense (>80% cover) forest. As the distance from (built-up, cropland, and roads) increases, the likelihood of finding the African forest elephant, indicating that species distribution is adversely affected by the factors. The elephant presence probability increases close to rivers and reduces as the distance increases but maintains a moderate distance to stream. As elevation decreases, the likelihood of finding the species occurrence increases. This species preferred temperature is 25 °, but preferences decrease sharply at higher temperatures.

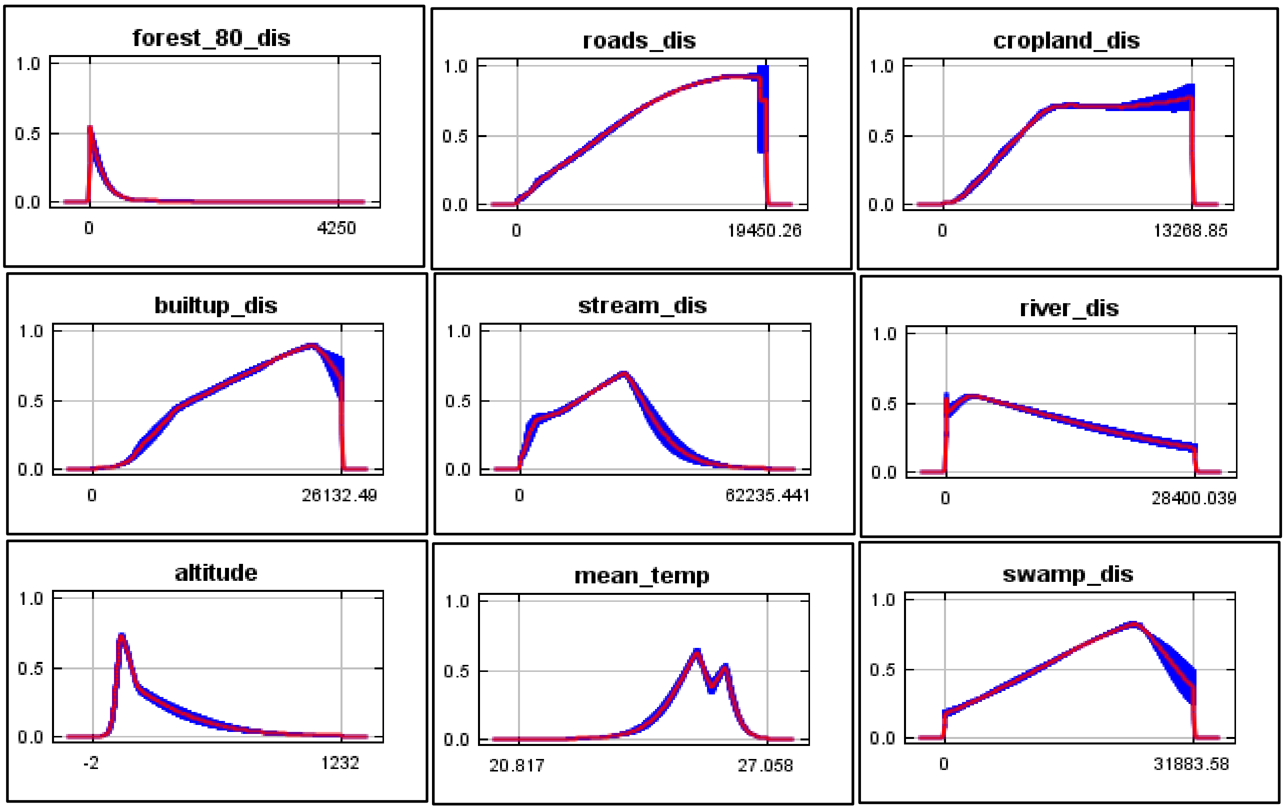


Figure 14 African forest elephant model response curve

From the response curves of the Pygmy hippopotamus (Figure 15), as the distance from (cropland, roads, and built-up) increases, the higher the probability of finding the species occurrence. The distance where the probabilities reach the maximum is shorter for the cropland and roads, longer for the built-up areas indicating the intensity of human-wildlife conflict in those land uses. The species prefer being closer to the swamp, as indicated by the response curves. The variable (distance to stream) demonstrates that as the distance from the stream gradually increases, the likely the chances of finding the species presence increase from 0.50 to 0.60. Based on the variable mean annual temperature, the species prefer a temperature at 25^{o}; anything higher is unfavorable.

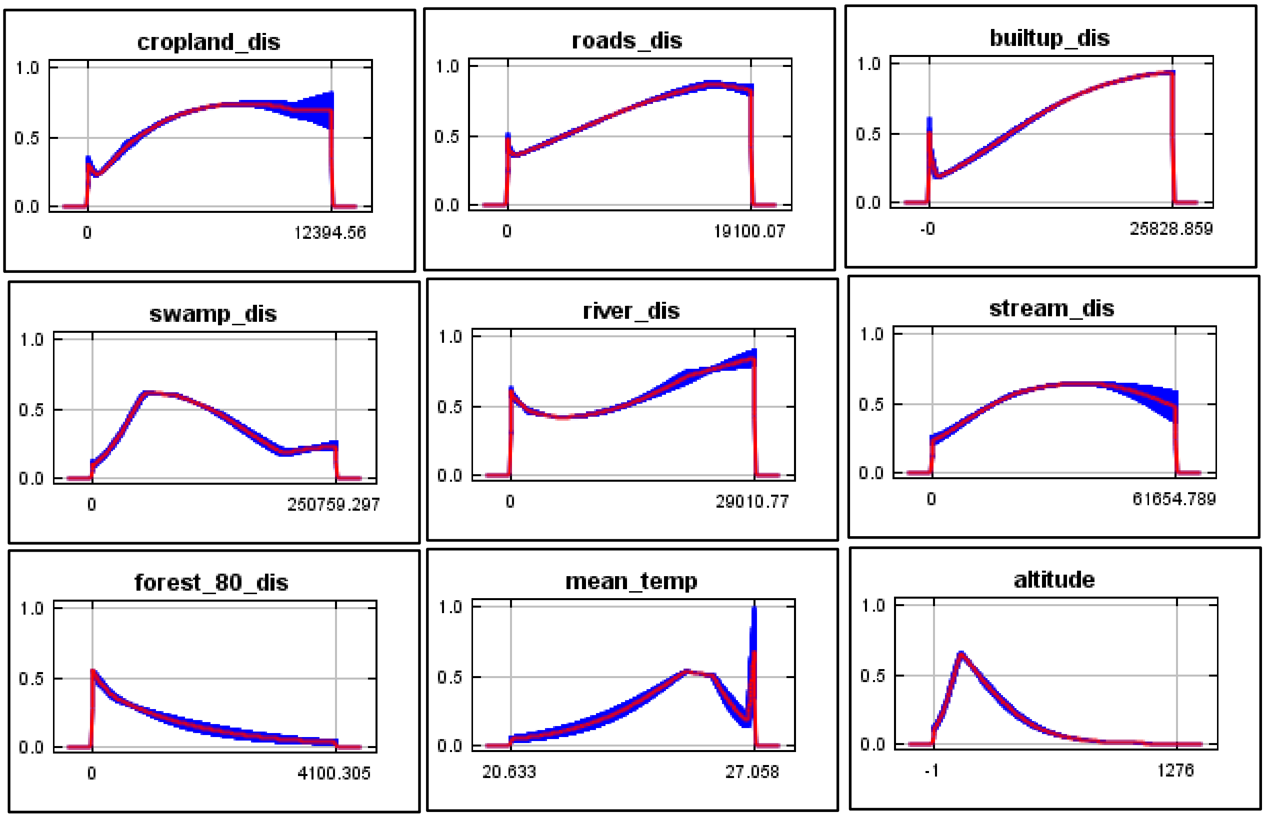


Figure 15 Pygmy hippopotamus model response curves

3.5 Predicted suitable habitat in Liberia and its protected status

As displayed in (Figure 16), the predicted pygmy hippopotamus suitable habitat within the country was 25,445 km^{2,} accounting for 27% of the country's total area. Of the country's 25,445 km2 of suitable habitat, 5,130 km^{2,} accounting for 20%, falls within the boundary of protected areas. Likewise, the total suitable habitat distribution of the African forest elephant in Liberia is predicted to be 8,466 km^2 representing 8% of the entire country’s area. Of this predicted area, African forest elephant suitable habitat is 2,745 km^2 representing 32%, within the boundary of the protected area.

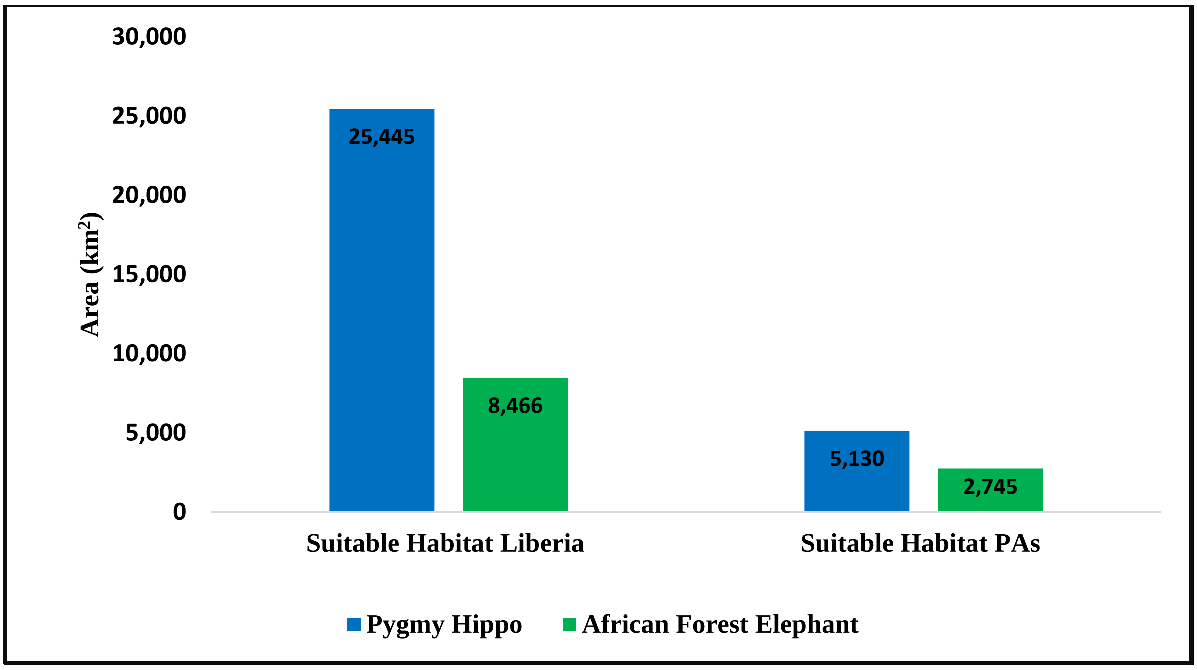


Figure 16:Estimated species coverage in and out of protected areas

3.6 Protected area suitable habitat capacity to sustain viable species population

As the predicted suitable habitat map overlaid with protected areas boundary was generated, an analysis metric (Table 9) was calculated for Liberia. This was done to determine the carrying capacity of predicted species suitable habitat in each protected area to maintain a long-term viable population of both species. From the analysis, the Sapo protected area holds the highest suitable habitat 1227 km^2 and 1507 km^2, respectively, for both species, with the estimated population that can be sustained for each individual resulting to (Elephant =245 and Pygmy hippo = 2486)—followed by the Gola protected area with a suitable habitat of 701 km^2 and 825 km^2 individually. (Elephant = 140 and Pygmy hippo = 1361) are the estimated population's suitable habitat capable of sustaining.

Considering the Foya and Gbi protected areas, suitable habitat was estimated to be 282 km^2 and 378 km^2 for the African forest elephant, which is projected to house 56 and 75 individuals. Little or no suitable habitats for the African forest elephant were predicted in the Bong, East, West Nimba, and Wologizi protected areas. The East and West Nimba protected areas, in particular, are isolated from the rest of the country's PAs. Notwithstanding, most of the protected areas in the country performed well in hosting suitable habitat for the Pygmy hippopotamus, except the East and West Nimba isolated protected areas, which don't have suitable habitat for the species sustenance based on the model prediction.

Table 8:Estimated species sustenance within protected areas

PAs Names	Elephant suitable habitat (km2)	Species population sustenance	Hippo suitable habitat (km2)	Species population sustenance
Cestos	35	7.1	102	168.3
Grebo	7	1.3	759	1252
Gola Forest	**701**	**140**	**825**	**1361**
Foya	282	56	518	854
Kpo	1.2	0	178	293
SAPO	**1227**	**245**	**1507**	**2486**
Grand kru	86	17	433	714
Gbi	378	75	697	1150
Bong	-	-	10	16
East Nimba	-	-	1	1
West Nimba	-	-	-	-
Wologizi	-	-	52	85

3.7 Optimum locations for corridor establishment in Liberia

As connecting the protected areas is essential for other species, the least cost path analysis result identified seven (7) optimum locations in the northwestern block, a single location in the North, and seven (7) locations in the southeastern block for corridor establishment (Figure 17). As the results show, corridor establishment was not possible between the Cestos and Grand kru protected areas. Additionally, it is challenging, if not impossible, to connect protected areas in the northwestern and southeastern blocks of the country due to gap in the center of the country. Consequently, this is predominantly due to unsuitable habitats in the center of the country for both species, especially the African forest elephant (Figure 5).

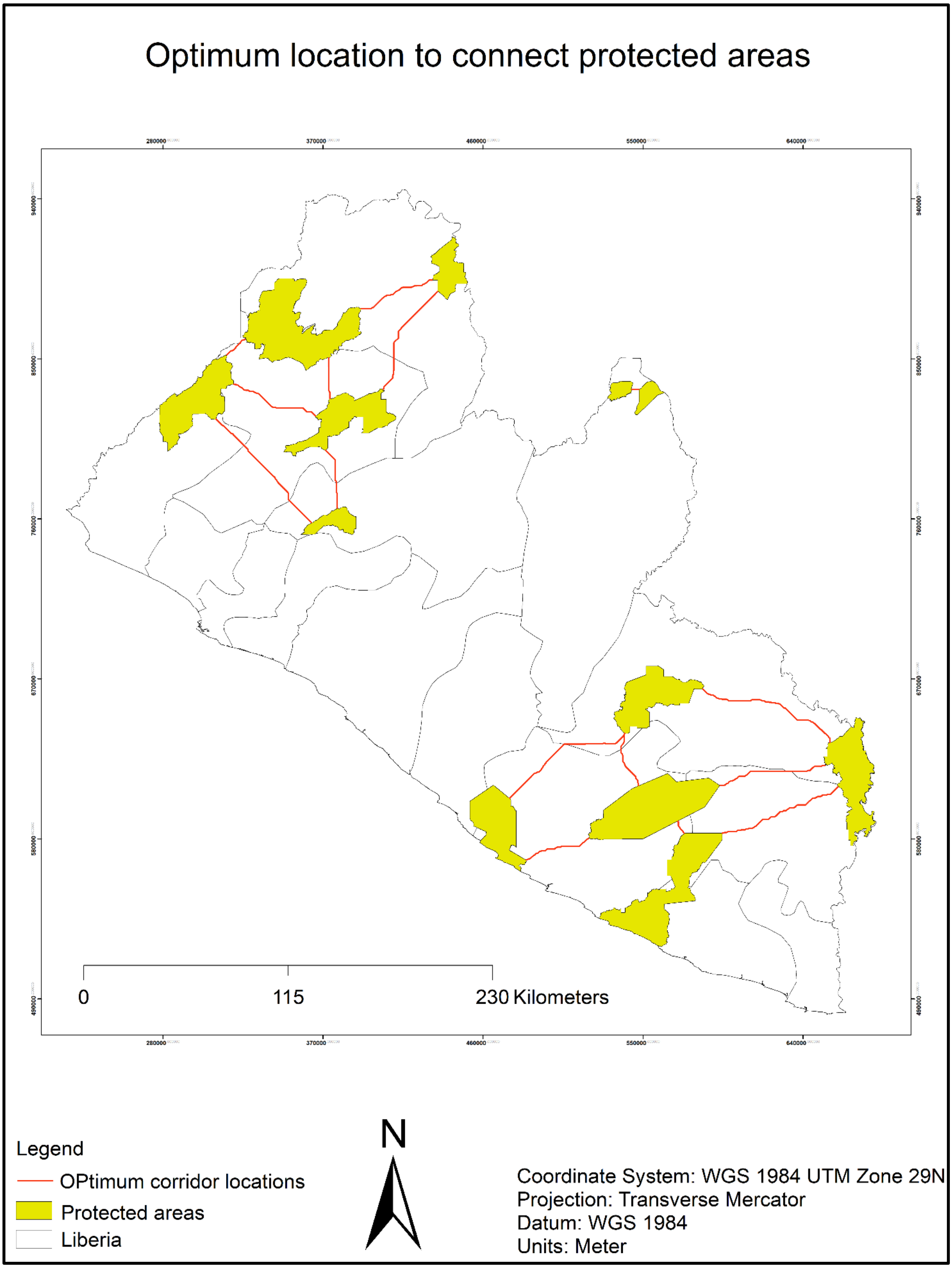


Figure 17: Optimum location to connect protected areas

From the analysis to connect selected species, suitable habitats that are protected (Figure 18). The analysis results for African forest elephant identified a single location between the two suitable habitats in the northwestern block. Five optimum locations were identified between suitable habitats in the southeastern block, connecting the Sapo PA, which hosts the largest suitable habitat with other habitat patches for corridor establishment. For the Pygmy hippopotamus, there were four (4) optimum locations in the northwestern blocks and eight (8) in the southeastern block for corridor establishment, respectively. Within the Gbi protected area, a single in-situ location was identified to connect the two individual suitable habitat patches as they are separated.

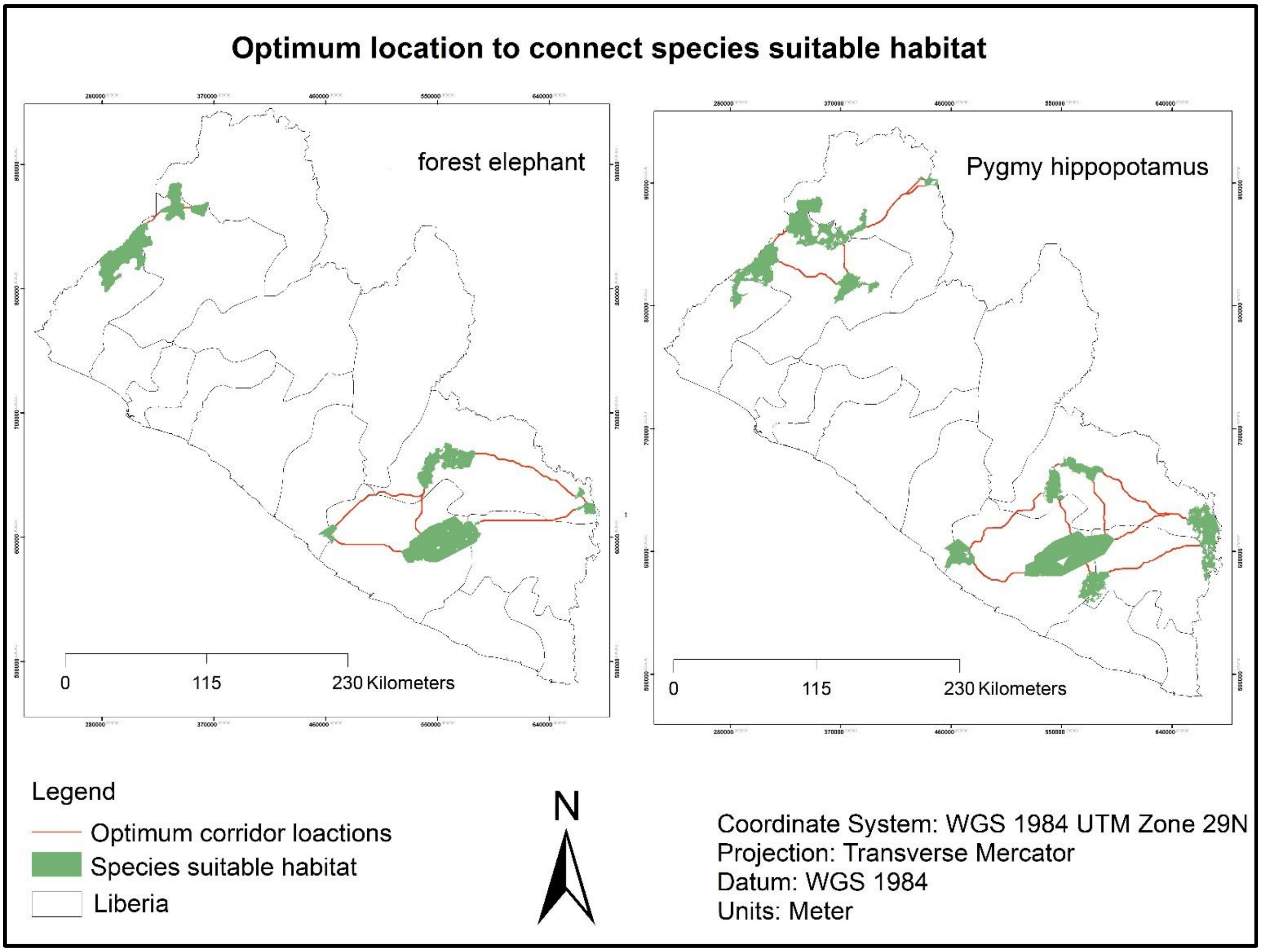


Figure 18: Optimum location to connect species suitable habitat

4. DISCUSSION

4.1 Potential distribution of species suitable habitat in Liberia

As the importance of protected areas is to protect endangered and rare species by covering those habitats that are suitable for the species sustenance. The results of this study provide essential information to that effect based on models generated in maxent for the two selected umbrella species. Based on the model output from the African forest elephant and Pygmy hippopotamus, suitable habitat was confined in the country's northwestern and southeastern forest block (Figure 5). To some extent, this was expected as most observation points of both species were located in both forest blocks. This finding agrees with (Boafo & Sani, 2011; International, 2013; Johnson, 2015) results, which identified these locations to harbor these species.

Regarding the model's performance (Figure 6&7), both models performed well with both species models AUC is ≥0.8 (Rebelo *et al.,* 2010). Compared to the model prediction of the same species in the Upper Guinea forest by Freeman *et al.*,(2019), which used EVI as environmental variables for model prediction. This study model's accuracy is probably high due to additional environmental variables that affect and reflect the species environmental preference and distribution (Austin, 2002; Austin, 2007). Ficetola *et al.,* (2014), further mentioned that a model built with relevant environmental variables improves model prediction.

Freeman *et al.,* (2019) modeled these species spatial distribution using EVI as an environmental variable. Although it can aggregate the variability of climate, land use/land cover, and water availability for vegetation, a vegetation index derivative such as EVI. However, it cannot address animals' movement (and thus observations) with extensive home range, such as elephant species, between suitable and unsuitable habitats. Therefore, the present study is an effort to address that by using the "distance to" suitable habitat as an explanatory variable in addition to these species' distribution modeling in the country. As Bucklin *et al.*, (2015) noted, no best variables contribute to a more accurate species distribution model than other variables. As such, it can be stated that this model prediction is not the best for modeling these species but serves as an addition to model prediction.

Relating to the variable's contribution to the model's prediction based on the jackknife, in the African forest elephant model, based on model results, distance to built-up, cropland, and roads variables are the driving factors of species distribution (Figure 8). This is evident as the probability of finding the species increases as the distance from these variables increases (Figure 14). This relation is most likely due to disturbances, such as; hunting, poaching, and logging, as a form of activity. Tweh *et al.*, (2015), mentioned that hunting and mining are some of the major drivers of species habitat depletion in the country. From the Pygmy hippopotamus jackknife (Figure 11), distance to built-up and cropland was also the influencing factor to the model prediction. This is most likely due to the anthropogenic factors mentioned above. Following these variables is the distance to the swamp, which is expected as the swamp is one of the species' preferred habitats. The majority of the species trail location was confirmed to be located along swamps, streams, and rivers in the Upper Guinea forest (Hillers *et al.*, 2017). Surprisingly, the variable's distance to forest did not perform as anticipated for both models' predictions, as both species, especially the African forest elephant activities, are associated with forest. Therefore, histograms for both species were plotted (Figure 9&12) as mentioned previously against the distance to built-up variable (Figure 10&13) to assess the findings.

Based on the plots, it was identified that majority of the species observations distribution in the forest has a value of zero compare to distance to built-up, which has almost a better distribution with distance. Consequently, this could be one reason of distance to forest low contribution. As there is insufficient environmental gradient to train the model, notably, the model is built as a function of species presence and ecological gradient. As Elith & Franklin (2013) mentioned, no model can "invent" information that is not represented in the data for computation. This could be the case for the forest as it is impossible to accurately compute Euclidean distance to the forest when a majority of the observations are in the forest compared to built-up. Therefore, this sampling bias is potentially one of the causes of distance to forest low contribution the model.

Another reason for the lower than expected contribution of the **dense** forest (>80% tree cover) in modeling the distribution of species is that species might occupy open forest areas equally well. As a consequence, other non-forest land cover variables used in the present study capture better species environmental niches. The mapping typology and accuracy itself are another reason that the Geoville dense forest layer did not explain species presence to a larger degree. For example, there is an information gap in the classes of open forest of 30-80%, and <30% tree cover, as the land cover between these classes is lacking. Consequently, as Bradley & Fleishman (2008) mentioned, categories of such land cover classification may have a low contribution to model predictions, especially when the classes are heterogeneous in nature.

4.2 Protection status of species suitable habitat and carrying capacity (Gap)

Based on the model prediction, the African forest elephant's suitable habitat distribution in Liberia is 8,466 km^2 and Pygmy hippopotamus 25,445 km^2, primarily situated in the South-eastern and North-western block of the country (Figure 16). A fraction, 32% African forest elephant and 20% Pygmy hippopotamus, have protection status from these predicted suitable habitats. Consequently, this leaves the rest of the species' suitable habitat unprotected. This aligned with Tweh *et al.*, (2015), a nationwide survey that uncovered that most large mammals don't have protected status. This thus leaves these species' habitats vulnerable to destruction and infringement, leading to extinction as they are labeled as endangered mentioned previously.

It is evidenced that significant causes of biodiversity loss in Liberia are primarily bush meat hunting and poaching (Tweh *et al.*, 2015). This threat to these species and their habitat extends to activities from agriculture, logging, and illegal logging, and commercial plantation, which replaces forest cover with rubber and palm oil mentioned by Hodgkinson *et al.*, (2013). This further includes the increasing wave of investment in the mining sector (Primack, 2010; Johnson, 2015). Therefore, this leaves other species vulnerable to threats highly alarming as these umbrella species habitats extend to other species in the country. As such, conservation urgency is needed base on the gap in protection.

Based on the fraction of species' suitable habitat with protection status, their carrying capacity was assessed to identify the population they can sustain (Table 9). The carrying capacity was assessed based on the species' suitable habitat (km^2) and population density (individual per km^2). From the African forest elephant assessment findings, the Sapo protected area can sustain a population of 245, Grebo 140, in the Gbi 75, including Foya 56 and Grand Kru 17, respectively. The rest of the protected areas had little or no suitable habitat to sustain a viable population. The Sapo and Grebo protected area population agreed with Sukumar & Daniel (1995) simulation on Asian elephants, which recommended that the probability of population surviving 100 years should be greater than 100 individuals. This guide is used because Asian elephants and African forest elephants have similar characteristics and habitat pressure (AfESG, 2005). Based on this recommendation, suitable habitats in other protected areas are insufficient to sustain a viable elephant population for $\geq$ 100 years in Liberia.

From the Pygmy hippopotamus assessment, the Sapo and Grebo had the most suitable habitat to sustain viable species populations. This is not surprising as these were locations the species presence was observed. The protected areas with the lowest population that can be sustained are Bong, East, West Nimba and Wologizi, with the rest having an estimated population greater than 100.

Now, there is no set value on the minimum viable population that is recommended for long-term protection for Pygmy hippopotamus; however, based on the estimated figures, these habitats are likely to sustain genetically viable populations of species. This relates to the expectation express by Reed *et al.,* (2003) that a viable population ranges from 50 to 10 000 individuals in general.

4.3 Optimum location for corridor establishment in Liberia

As the study estimated the species population, each suitable habitat in a protected area can sustain over time; it is necessary to establish a corridor to foster genetic flow between populations through species dispersion. As it helps prevent species extinction potentially due to inbreeding and loss of genetic diversity, including environmental factors as a major conservation concern for other species (Reed *et al.,*2003;Flather *et al.,* 2011). Therefore, from the analysis of optimum location for all protected areas in the country, both species resistance layers average was generated. From this average, a single optimum location was identified in the country for corridor establishment. The model identified 15 optimum locations amongst protected areas for corridor establishment (Figure 17). Based on the analysis, no optimum location was identified to connect the Cestos and Grand Kru protected area. This is probably due to the higher resistance cost for species dispersal. This resistance to species dispersal is mentioned by Johnson (2015), stating that most of the area in this location is communal land.

However, this result is opposite to (Freeman *et al.,*2019) results that produced individual corridors for all modeled species. However, identifying these optimum locations for corridor establishment is essential for Liberia’s biodiversity conservation. Notwithstanding, these corridors in this study align with the six -national reports of Liberia (2019) recommendation for protected area connectivity. Additionally, the research analysis identified an optimum location to connect both species suitable habitats capable of sustaining individuals’ species (Figure 18). These results are partially consistent with previous studies on these species' connectivity in Liberia (Freeman *et al.,*2019). Apparently, there is a considerable gap in connectivity between the protected areas in the northwestern and southeastern block of the country, especially for the African forest elephant, as there are no suitable habitat patches to serve as a steppingstone to connect them considering the species dispersal ability. Therefore, given the intention of Liberia to expand the protected areas in the country, restoration of degraded forest could be further explored to act as steppingstones for connecting the north and south protected areas (also with the rest of the Guinean forest).

4.4 Challenges and limitation of the study

The optimum way to achieve the objectives set in this study is to collect primary presence points within Liberia. Obtain accurate data using an appropriate sampling strategy is essential for modeling species. However, this research had to rely on existing species observations (gbif database) due to the time allocated. These challenges also extend to the outbreak of covid-19 at the time of this study as it altered any potential field visit. The use of this data may incur inaccuracy in the model potentially due to sampling bias (Barbet-Massin *et al.*, 2012). This affects prediction as, without accurate sample representation of species habitat, the model will compute an unknown combination of a biased sample (Elith & Franklin, 2013).

Given the method used to assess the estimated population, suitable habitat within protected areas can sustain. Notwithstanding, this method constitutes a disadvantage primarily due to the population densities used for estimation. These population densities were taken from available records published from literatures from years ago. Considering this temporal aspect, lots of stochastic factors have occurred affecting these species' population densities. Thus, affecting the values produced in this study in relation to current reality.

The land covers data used in the study may have some classification accuracy limitations that may affect modeling output that should be acknowledged. As mentioned previously, there is an information gap in the classes of the open forest of 30-80%, and <30% tree cover, as the land cover between trees, is not explicit, such as giving a clear differentiation between plantations and natural forest. Therefore, this can provide a false impression of precision in reality. Additionally, land cover classes could be affected as a result environmental layers aggregation during the pre-processing stage of the study.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusions

The main objective of this study is to assess the representativeness of species suitable habitat in Liberia's protected area using the modeled spatial distribution of two umbrella species. A general assumption of this thesis is that by protecting sufficient habitat areas for these two umbrella species, other species will also be protected as their habitats is an umbrella. This effort is highly needed, as uncovered in this study. Moreover, modeling these species in Liberia using these additional variables that considered human activities is an added improvement to model prediction. Furthermore, based on the research questions, the below conclusions were drawn.

5.1.1 Where are the suitable habitats of *Loxodonta cyclotis* and *Choeropsis liberiensis* in Liberia?

The analysis discovered that the majority of the two species' suitable habitat is situated in the northwestern and southeastern blocks of the country, where most of the protected areas are located. Form the two species suitable habitats; the African forest elephant habitat is more limited compared to the Pygmy hippopotamus, leaving little room for dispersal.

5.1.2 Which environmental variables perform best in predicting the selected species' suitable habitat?

Based on the model results, variables that influence the African forest elephant distributions in the country the most are distance to built-up, cropland, and roads; all of these variables have a negative relationship with African forest elephant. The Pygmy hippopotamus is the distances from built-up, cropland (negative relationship), and swamp areas (positive relationship). For the two models, distance to the forest had little contribution unexpectedly, as their habitat is associated with forest primarily. However, further exploration uncovered that most of the species samples were in the forest, thus affecting the Euclidean distance computation by the model was identified as one reason.

5.1.3 How much of the potential distribution and suitable habitat of *Loxodonta cyclotis and Choeropsis liberiensis* is covered by the protected area network?

As discovered, there is a gap in protection as only a small section of suitable habitat is being protected. This section with protection status is 2,745 km2 out of 8,466 km2 of suitable habitat for the African forest elephant and 5,130 km2 out of 25,445 km2 of suitable habitat. This is therefore leaving a gap in these species protection as their habitats are insufficiently represented.

5.1.4 Are predicted suitable habitats in protected areas of sufficient size to sustain viable populations of the selected species?

Of the fraction suitable habitat with protection status, only the Sapo (245) and Gola (140) protected area can sustain a viable population of the African forest elephant over a hundred years periods As for the Pygmy hippopotamus, most suitable locations in protected areas can sustain a viable population, as they are greater than a hundred (100) individuals.

5.1.5 Given Liberia protected areas designation, where are the optimum location for corridors establishment?

To establish an ecological network between protected areas in order to enhance species dispersal ability and facilitate genetic flow. Fifteen (15) optimum locations for corridor establishment were identified within the country in general. However, no optimum location was identified to connect Cestos and Grand Kru protected areas due to high resistance cause primarily by activities in that region. Additionally, no optimum locations were identified to connect species suitable habitat in the northwestern and southeastern blocks.

5.2 Recommendations

This study improves increases scientific knowledge on modelling the distribution of two umbrella species in the country using an existing set of relevant environmental variables. Comparing this study to previous and proposing future studies will improve analysis for species distribution and conservation in the country. The following recommendations need to be taken into consideration:

- Future modeling research in the country should consider variables that reflect factors affecting these species distribution, especially human activities and disturbances, such as; distance to built-up, cropland, and roads.
- Evenly distributed observations collection in the country is done to reduce bias during model prediction when using Euclidean distance variables in the model.
- Additional protected areas are established in a suitable habitat without protection status to optimize species protection.
- Future efforts should consider connecting the northwestern and southeastern protected areas to expand species genetic pool by restoring the degraded forest in the center of the country.

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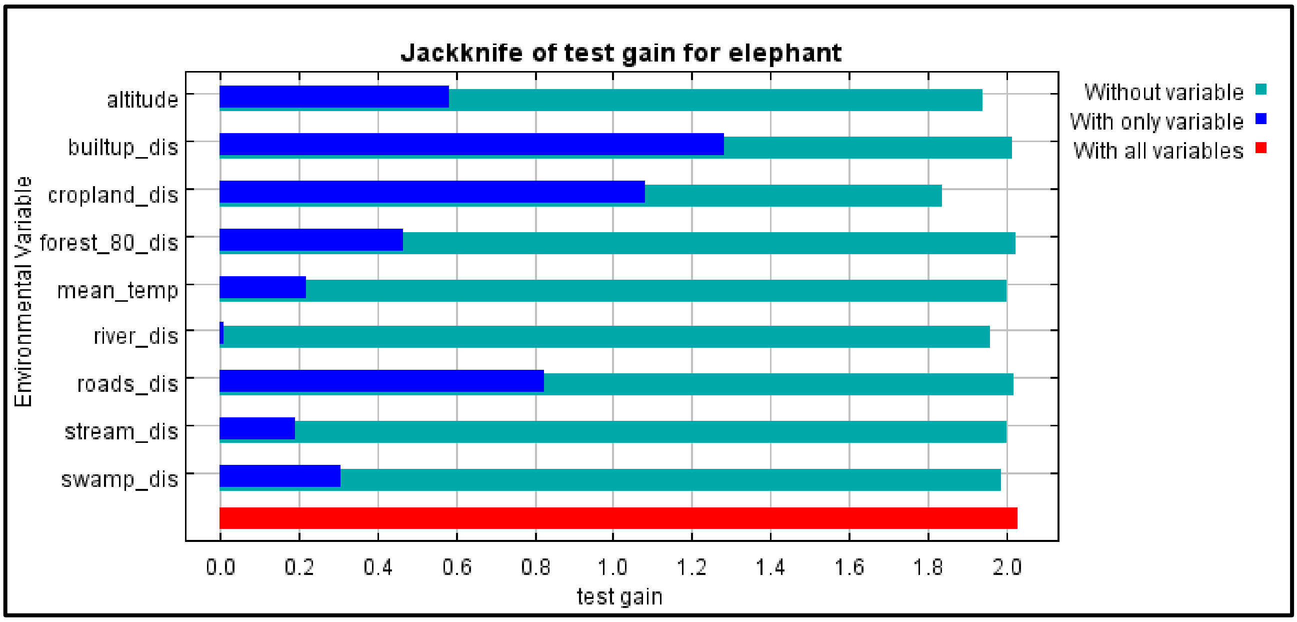
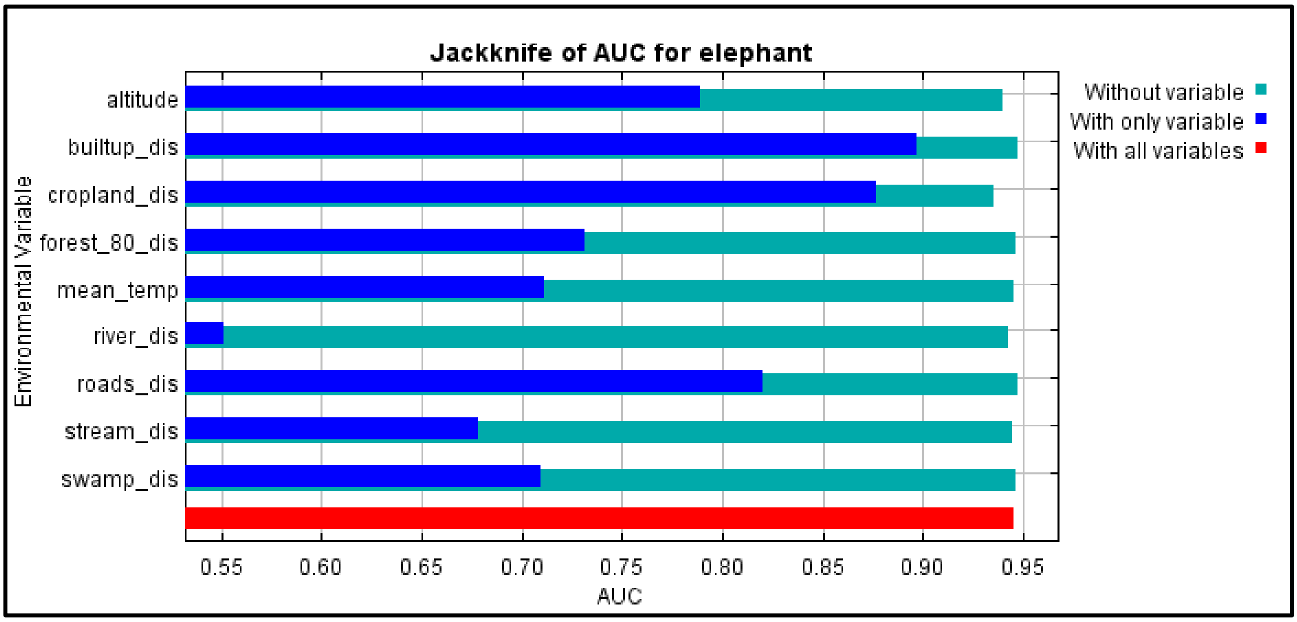
6. APPENDICES

Appendix 1: African forest elephant Jackknifes

Jackknife test gain

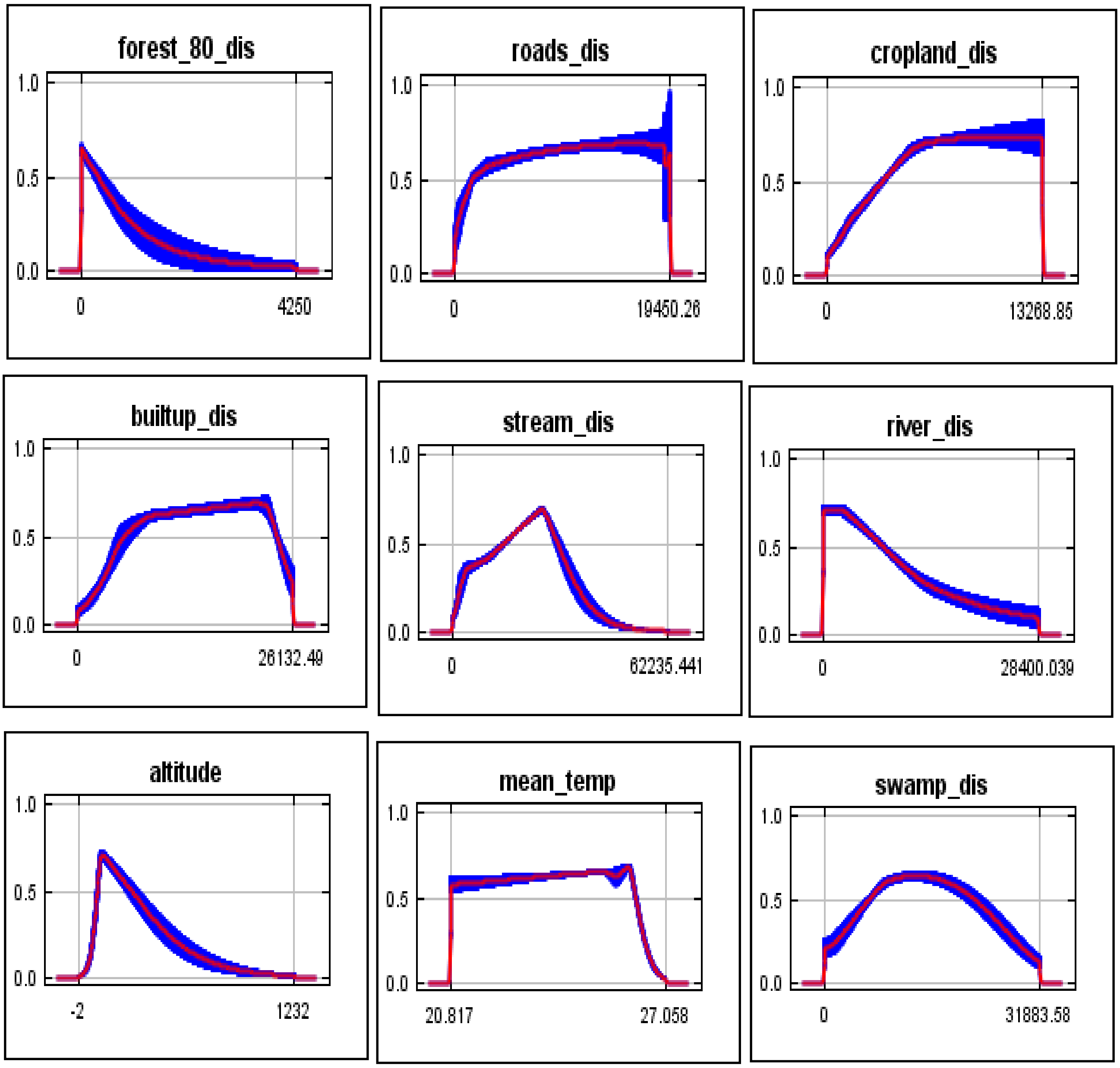


Jackknife of AUC



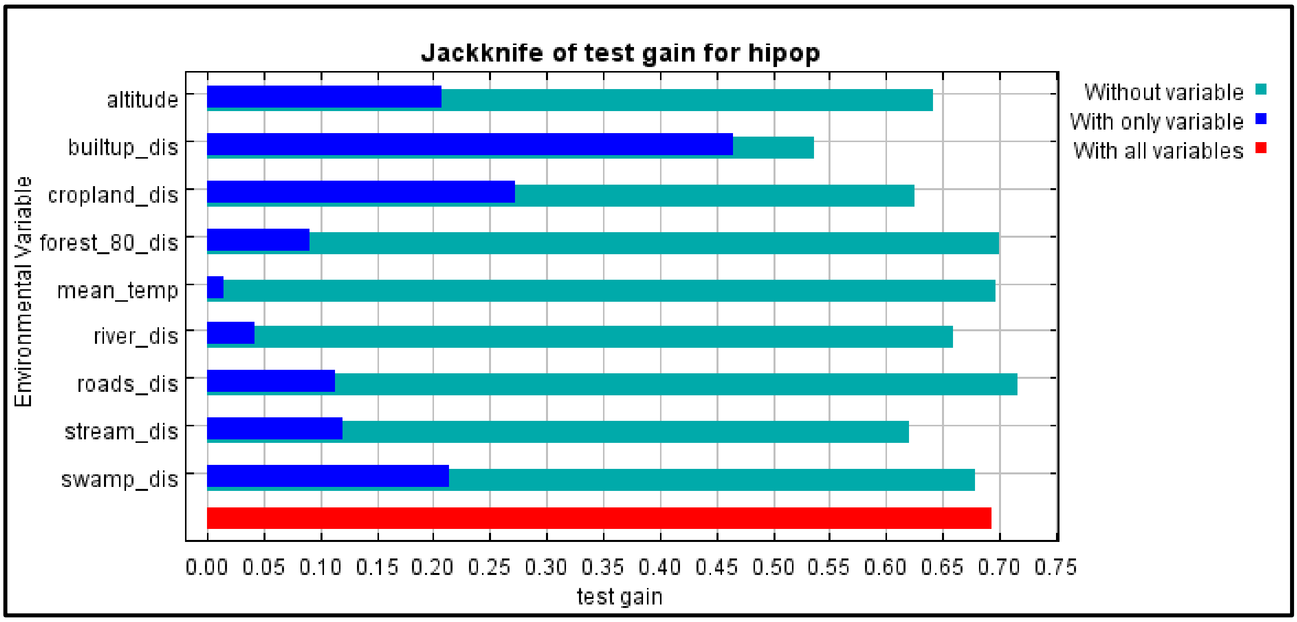
Appendix 2: African forest elephant

Response curves of all environmental variables used in creating the model

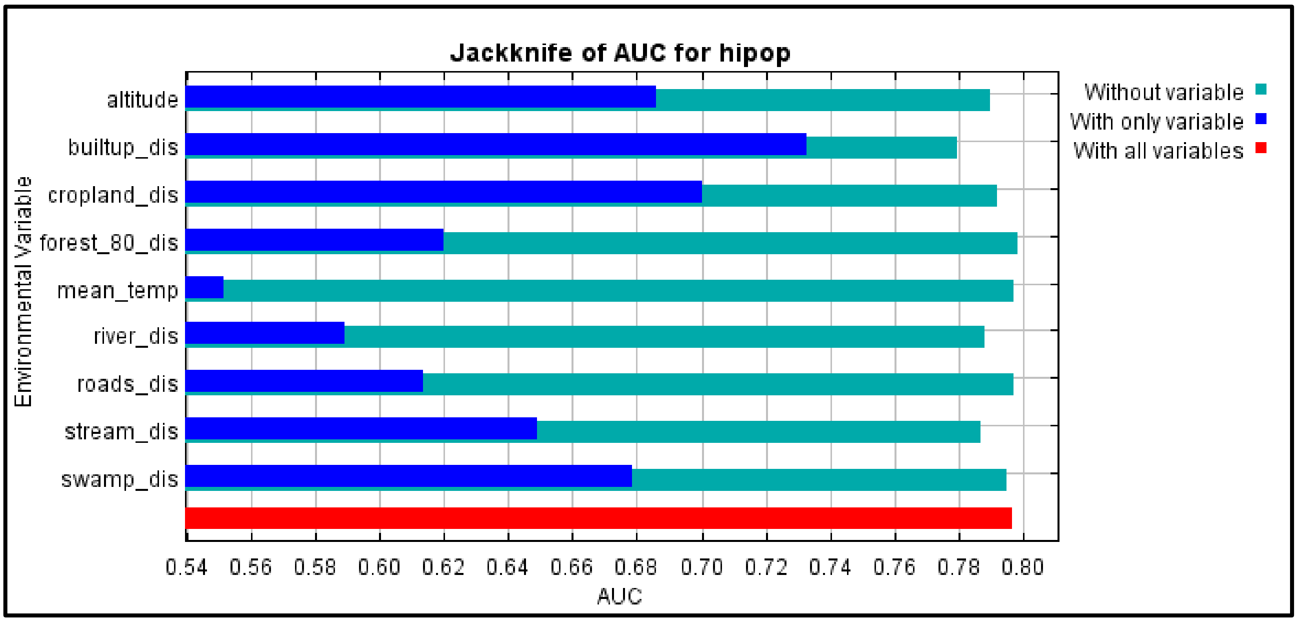


Appendix 3: Pygmy hippopotamus Jackknifes

Jackknife test gain



Jackknife AUC



Appendix 4: Pygmy hippopotamus

Response curves of all environmental variables used in creating the model