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Forest loss during 2000–2019 in pygmy hippopotamus (*Choeropsis liberiensis*) habitats was driven by shifting agriculture

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Summary

The Upper Guinea Forest (UGF; West Africa), a global biodiversity hotspot, has lost more than 90% of its original area since 1900, threatening endemic species such as the endangered pygmy hippopotamus (*Choeropsis liberiensis*). However, little is known about the proximate causes of this deforestation. We classified Sentinel-2 data using the random forest algorithm to differentiate between three main human processes (shifting agriculture, intensive agriculture or urban expansion) driving deforestation between 2000 and 2019 across the pygmy hippopotamus distribution area. Out of c. 89 600 km^2 in the year 2000, 15 900 km^2 (17%) of forest were lost, primarily to shifting agriculture (14 900 km^2). Côte d'Ivoire and Liberia accounted for 14 900 km^2 (94%) of the net area of forest lost, c. 15 times greater than deforestation in Sierra Leone and Guinea combined (953 km^2). Forest loss inside protected areas is pervasive, and it is essential to prioritize conservation efforts in areas where deforestation is still low (e.g., Taï, Sapo and Gola Rainforest national parks). We suggest that the preservation of the UGF will face challenges associated with people's demand for food and income. Continued landscape-scale planning and action to reduce deforestation are urgently needed to limit the impact of shifting agriculture on pygmy hippopotamus habitat.

Introduction

The Upper Guinea Forest (UGF) in West Africa is one of the last remnants of tropical rainforest in the region, supporting more than 9000 species of plants and c. 1800 species of vertebrates (Liu et al. 2016). This includes animals listed as Endangered in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, such as the pygmy hippopotamus (*Choeropsis liberiensis*; Ransom et al. 2015, Ola & Benjamin 2019). Owing to high species endemism and rapid forest loss, the UGF is considered a biodiversity hotspot, but forest loss and degradation have continued (Myers 1988, Mittermeier et al. 2004, Curtis et al. 2018).

The UGF is widely fragmented due to human population growth and the expansion of extractive industries, plantations, logging and slash-and-burn agriculture (Hosonuma et al. 2012, CILSS 2016). The UGF once extended over more than 620 000 km^2, from Guinea in the east to Nigeria in the west, but unregulated activities such as logging and shifting agriculture were responsible for c. 90% of the forest loss between 1999 and 2013 (Bakarr et al. 2004, CILSS 2016). Shifting agriculture, also known as 'subsistence agriculture', is common throughout the UGF region, and it is defined as the cultivation of small- to medium-scale crops maintained by smallholders (Hosonuma et al. 2012). Logging, agriculture and fire are also drivers of deforestation (Curtis et al. 2018). In the UGF region, Ghana lost c. 40% of its forest area between 1990 and 2010 (Hansen et al. 2013); Côte d'Ivoire, Gabon, Liberia and Nigeria have also reported large areas of deforestation since 2005, mostly due to illegal logging (Oduro et al. 2014). Large-scale crops of cocoa and oil palm are well-known drivers of deforestation in the UGF. For example, during 1989–2013, the area of oil palm plantations increased by 63% in Ghana and by 62% in Côte d'Ivoire, and more than 1 000 000 km^2 of forests and woodlands in the region are vulnerable to transformation into crops and other forms of development by 2080 (Vijay et al. 2016).

Agriculture is widespread in West Africa and is a major threat to the flora and fauna that inhabit the UGF, including the pygmy hippopotamus. In Côte d'Ivoire, for example, agriculture occupied c. 84% of the usable land until 2016 (Ruf et al. 2015, CILSS 2016). Some 60% of the 37 300 km^2 of tropical forests that existed in Côte d'Ivoire in 1975 was lost to shifting and industrial agriculture (CILSS 2016). These rates of forest loss have provoked drastic declines in endemic populations of flora and fauna in the region (Grelle 2005, Di Marco et al. 2016, Vijay et al. 2016).

Conversions from forest to agricultural land reduce usable habitat, increase fragmentation and limit species movement (Foley et al. 2005, Gibson et al. 2011). For the endemic pygmy hippopotamus, forest loss has contributed to a sustained, region-wide population decline, and further forest loss may drive the species to extinction. Understanding the activities that lead to forest loss in the UGF is therefore critical for the conservation of this and other species. Between 1982 and 1986, there were 19 000 pygmy hippopotami in the region, but by 1997 the wild population consisted of fewer than 5000 individuals (Ransom et al. 2015). Some of this decline was related to hunting for bushmeat and other purposes during times of internal conflict in the region (Conway 2013, Conway et al. 2015). The pygmy hippopotamus population may now be only 2000–2500 animals (Ransom et al. 2015). Pygmy hippopotami are restricted to primary and secondary forests with high canopy cover, prefer locations close to water bodies and are rarely found in disturbed areas (Eltringham 1999, Lewison & Oliver 2008, Eshuis 2011); the animals rely on relatively well-preserved forests to survive, and those conditions are found in some protected areas in the UGF.

Even though forest loss in the UGF is probably the major cause of the pygmy hippopotamus population decline, the spatial distribution of the drivers of forest loss in this area remains largely unknown. A driver of forest loss is an activity or process that changes a land with trees to a land without trees (Curtis et al. 2018). Understanding such activities is crucial for planning, infrastructure and conservation policies that consider the needs of human communities and endangered species in the UGF. Deforestation is prevalent in the UGF (CILSS 2016); however, spatially explicit information on the proximate drivers of deforestation within the pygmy hippopotamus's range is still scarce. Remote sensing has enabled the drivers of forest loss to be investigated at global and continental scales. For instance, shifting agriculture was the main driver of forest loss in sub-Saharan Africa between 2001 and 2015 (Curtis et al. 2018). However, the spatial resolution of this global analysis, for which the minimum pixel size is 250 m, limits its ability to reveal the proximate drivers of forest loss at finer spatial scales. Our study uses 10–m resolution imagery and proposes a remote sensing classification approach to identify contemporary drivers of tropical forest loss within the range of a threatened species in a region with persistent cloud cover. Assessing the drivers of deforestation is critical for informing conservation efforts for cryptic species such as the pygmy hippopotamus and other large mammals, for which their survival is strictly linked to well-conserved forests (Bowler et al. 2020). We used Sentinel-2 satellite imagery and the Hansen forest loss dataset (Hansen et al. 2013) to assess proximate deforestation drivers in the pygmy hippopotamus distribution. Specifically, we sought to: (1) identify the main proximate drivers of forest loss in the pygmy hippopotamus's range; (2) estimate the extent and distribution of forest loss related to each identified driver; and (3) estimate the amount of habitat loss inside protected areas in the UGF region within the pygmy hippopotamus's distribution area.

Materials and methods

Study area

The known distribution of the pygmy hippopotamus spans 140 221 km^2 across Guinea (2335 km^2), Sierra Leone (4814 km^2), Liberia (53 155 km^2) and Côte d'Ivoire (79 917 km^2; Fig. 1; IUCN 2015). Within this region there is a mixture of tropical and subtropical moist broadleaf forests, agriculture and human settlements. Rainfall occurs year round (range: 2200–5000 mm per year), with two long rainy seasons separated by two drier periods. Seasonal temperature ranges are 30–33°C during the dry season and 12–21°C during the wet season, with high humidity (≥70%) throughout the year. The natural vegetation is a combination of tropical–subtropical rainforests (closed-canopy forest, epiphytes, lianas and ferns) and tropical–subtropical lowland dry forest and thicket ecosystems (evergreen and drought-deciduous trees with some woody plants; CILSS 2016, Keith et al. 2022).

Data acquisition and processing

We identified areas of forest loss during 2000–2019 using the Global Forest Change dataset v1.7 (2000–2019; Hansen et al. 2013). We limited our analysis to areas with ≥50% canopy cover in 2000 (89 614 km^2) because pygmy hippopotami are mostly found in dense forests and rarely venture into areas with low canopy cover (Eshuis 2011, Bogui et al. 2016, Robinson et al. 2017). Owing to persistent cloud cover, we opted to use Sentinel-2 due to its higher temporal resolution, which provided more cloud-free pixels and, therefore, a greater number of clear pixels for further analysis (Fig. S1).

We used Google Earth Engine (Gorelick et al. 2017) to gather all available Sentinel-2 images corrected to surface reflectance (i.e., level 2A, 10–m pixels) acquired for the study area in 2019 (n = 3108; Copernicus Sentinel data, 2019). We followed Braaten (2021) to remove clouds and cloud shadows, then calculated eight spectral indices from image stacks to discriminate the different drivers of forest loss (Fig. S1 & Table S1). We developed a series of composite metrics to underpin our classification model of proximate drivers of forest loss within the distribution of the pygmy hippopotamus (Table S1); these metrics are frequently used for land-cover mapping to represent pixel-scale spectral dynamics that can be incorporated into statistical pixel classifications to discriminate different land-cover types (DeFries et al. 1995, Potapov et al. 2012). This process yielded a set of 182 covariate layers for use in the classification of the drivers of forest loss (Table S1).

Protected areas inside pygmy hippopotamus distribution

Our analysis focused on 'declared' protected areas according to the United Nations Environment Programme – World Conservation Monitoring Centre (UNEP-WCMC & IUCN 2021). There are 87 protected areas covering 30 669 km^2 that are partially or totally located inside the pygmy hippopotamus's range (UNEP-WCMC & IUCN 2021), and pygmy hippopotami are known to inhabit them (Roth et al. 2004, Collen et al. 2011, Garteh 2013, Conway et al. 2015, Bogui et al. 2016, Hillers et al. 2017, Ouattara et al. 2018).

Driver classification

We developed a classification scheme of potential drivers of forest loss across the region (Fig. 2). Initial testing of the classification

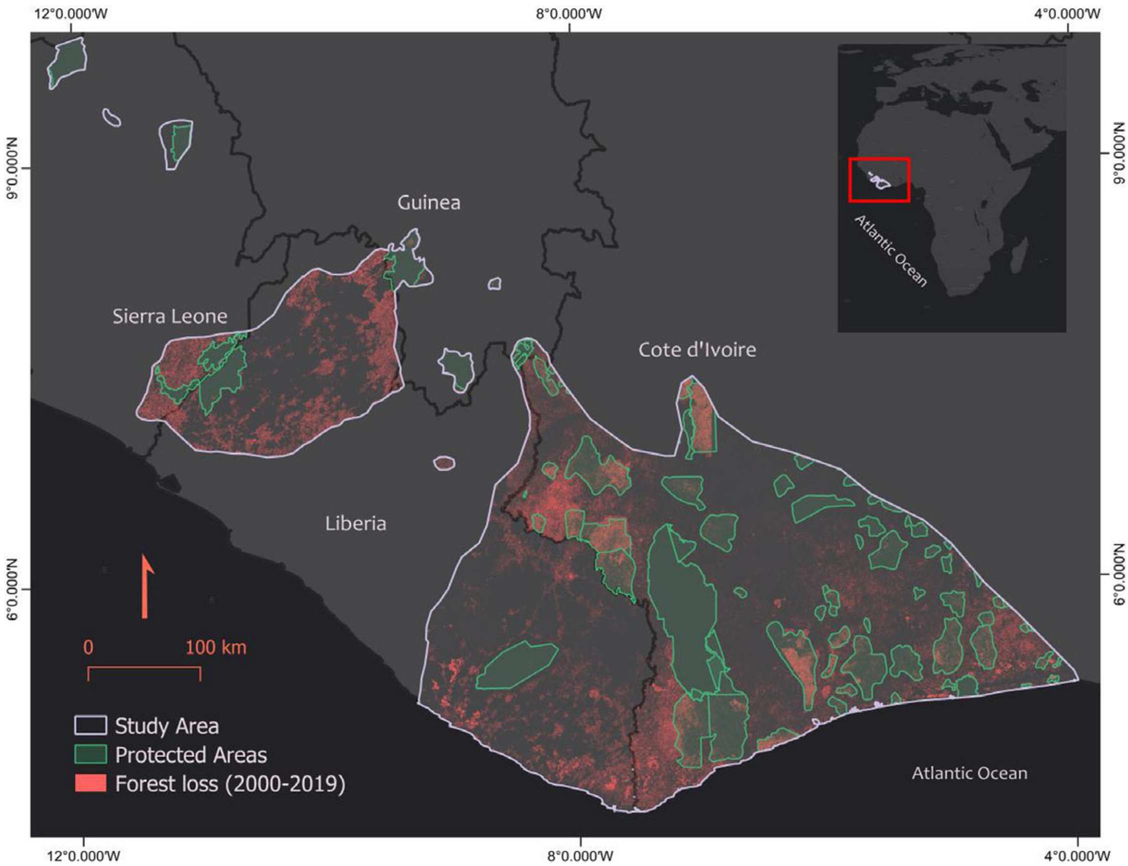


Figure 1. Diagrammatic map of the study area delimited by the distribution of Choeropsis liberiensis in the Upper Guinea Forest and encompassing parts of Côte d'Ivoire, Liberia, Guinea and Sierra Leone. Red pixels represent areas of 2000–2019 forest (≥50% canopy cover) loss in the study area. Data sources: Hansen et al. (2013), Ransom et al. (2015), UNEP-WCMC and IUCN (2021).

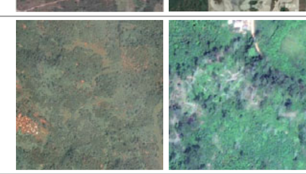
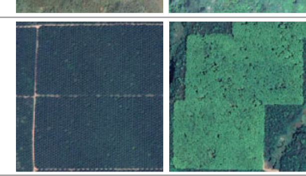
Driver class	Number of training points	Driver description from high-resolution imagery	High-resolution image
Urban expansion	250	In this region, built-up and urbanized areas are often surrounded by bare soil, therefore their spectral signatures are similar to those of mining concessions, roads, and other industrial activities and infrastructure. This class describes areas that have human settlements, built-up and urbanization features, human infrastructure, roads, mining, industrial activities and fire scars. Clear urban and industrial patterns visible, bare ground, barren lands.	
Shifting agriculture	450	This class describes features with similar spectral signatures, including: small scale farming, subsistence farming, grasslands, pastures, meadows, vegetation regrowth, temporary and small-scale permanent crops. In general, these are cleared areas surrounded by primary or secondary forests and shrublands. They appear as disperse patches across landscapes without distinctive patterns.	
Intensive agriculture	450	Large and distinctive plantation patterns, often tens or hundreds of hectares. This class describes areas that have industrial agricultural production systems. Includes fruit tree, oil palm, cocoa, coffee, and tea plantations, as well as forestry and agroforestry crops. Distinctive plantation patterns such as row planting, sharp farm edges.	

Figure 2. Definition of the drivers of forest loss and training classes alongside two examples of each driver from high-resolution imagery. High-resolution imagery and other interpretation cues were used to identify drivers of forest loss within the pygmy hippopotamus distribution. Pixels from Sentinel-2 images of these areas were selected for training and validating the classification model. Imagery sources: Esri, DigitalGlobe, GeoEye, CNES/Airbus, Maxar Technologies, USGS, Google Earth.

model revealed that the low number of cloud-free images over the study area, together with similarities in the spectral signatures of several drivers of forest loss, often resulted in driver misclassification. Therefore, we combined several driver classes into three driver categories that are informative of the drivers of forest loss in the UGF. The three categories are defined as 'Urban expansion', 'Shifting agriculture' and 'Intensive agriculture' (Fig. 2). While cattle grazing was not widespread in the UGF due to a range of

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diseases (National Research Council 1993), over 20 million people in West Africa now depend on livestock production and trade (Thébaud et al. 2018, Valerio et al. 2020). Cattle, buffalo, donkey, goat and sheep are common livestock in pastoral, transhumance and ranching practices in Côte d'Ivoire and Guinea, which combine livestock grazing with a range of crops (Inter-réseaux Developpment rural 2017, Valerio et al. 2020). Livestock grazing areas were merged into the 'Shifting agriculture' class because their spectral signatures and image interpretation cues were similar from satellite imagery. We used the full 2019 Sentinel-2 image archive supplemented by high-resolution imagery available in *QGIS* to develop training data for each driver class. In total, we acquired 1150 training points for all classes (Fig. 2) and 450 points for independent accuracy assessment (Figs 2, S1 & S2; Foody 2009). The training and validating points were collected by visually interpreting high-resolution imagery from Google Earth, Bing Maps and ESRI available in *QGIS*. The georeferenced training points correspond to the driver classification scheme of forest loss in our study area. We did not collect training data where high-resolution imagery was unavailable or in places where clouds were prevalent (e.g., southern Liberia and western Côte d'Ivoire).

Classification model

We used the Hansen et al. (2013) forest loss dataset to develop a mask of areas that had experienced forest loss in the region between 2000 and 2019. We used this mask to mask our covariate layers such that the model was deployed only in areas where recent deforestation has occurred (Table S1). A random forest classification model with 300 trees was used to classify these areas into one of the three drivers of interest. After applying the driver classification model, we post-processed the classified map with a majority (i.e., mode) filter to remove single, isolated pixels. Then, we computed the total area of each driver by country, both inside and outside protected areas. Accuracy was assessed using a confusion matrix; overall, pixels in the classified image were correctly assigned to drivers 87% of the time (overall accuracy). Class accuracies were high, with 'Urban expansion' achieving 96% accuracy, followed by 'Intensive agriculture' (86%) and 'Shifting agriculture' (81%; Fig. S2 & Table S2).

Results

In the year 2000 there were c. 89 600 km^2 of forest with 50% canopy cover in the study area. Côte d'Ivoire and Liberia accounted for 94% (14 948 km^2) of the net area of forest lost, c. 15 times greater than the forest loss areas of Sierra Leone and Guinea combined (953 km^2; Table 1). Côte d'Ivoire accounts for 57% of the pygmy hippopotamus distribution, out of which 9825 km^2 (61.8%) have been lost. Here, forest loss was concentrated in the north and south within the study area, as well as near the Liberian border, and was sparse in the central region (Fig. 3). Similar trends were detected in Liberia, where intense forest loss was evidenced in the southern and western regions of the country. Only 3.4% (4814 km^2) of the pygmy hippopotamus distribution falls within Sierra Leone's territory, of which 765 km^2 (4.8%) of forest were lost between 2000 and 2019. Out of the four patches that pygmy hippopotami are expected to inhabit, the most degraded lies on the border with Liberia (Figs 1 & 3 & Table 1). When normalized by the area within the pygmy hippopotamus distribution, Sierra Leone has lost more forest than Côte d'Ivoire or Liberia despite an order of magnitude difference in net loss, followed by Côte d'Ivoire, Liberia and Guinea (Table 1 & Appendix S1).

Our driver classification model indicated that almost all forest loss within the pygmy hippopotamus distribution is attributable to 'Shifting agriculture' (93.4%), with minor contributions from 'Urban expansion' (5.6%) and 'Intensive agriculture' activities (1%; Table 1). 'Shifting agriculture' activities account for 13 960 km^2 in Côte d'Ivoire and Liberia, whereas Sierra Leone and Guinea have lost fewer than 1000 km^2. 'Shifting agriculture' in Guinea has accounted for 170 km^2 out of 188 km^2 of forest loss, making it disproportionally large when compared to the other drivers assessed here (Table 1). In contrast, Côte d'Ivoire has lost almost two orders of magnitude more area to 'Shifting agriculture' activities (9019 km^2; Appendix S1).

Forest loss due to 'Urban expansion' was concentrated along the border, in western Côte d'Ivoire and north-eastern Liberia, with a small extent in Sierra Leone and Guinea (Fig. 3 & Table 1). Most of the 'Urban expansion' areas were associated with existing settlements, infrastructure and industries (e.g., mining) and were close to roads. We also found areas classified as 'Urban expansion' close to 'Shifting agriculture' and 'Intensive agriculture' patches, primarily in the form of land clearing for crops and infrastructure in oil palm plantations (Fig. 3 & Table 1). Within the pygmy hippopotamus distribution area, Côte d'Ivoire and Guinea were more impacted by 'Urban expansion' (0.88% and 0.73%, respectively) than Liberia (0.27%) or Sierra Leone (0.07%).

'Intensive agriculture' accounted for c. 1% (144 km^2) of the total area of forest loss, with most expansion occurring in Côte d'Ivoire and Liberia (Fig. 3 & Table 1). As the main crop in the 'Intensive agriculture' category, oil palm was easily identifiable from high-resolution satellite images and is thus considered to be one of the main industrial crops responsible for forest loss. This crop is primarily found in southern regions of Liberia and Côte d'Ivoire and extends from east to west in the pygmy hippopotamus distribution (Fig. 3).

Protected areas within the pygmy hippopotamus's range accounted for 30 669 km^2 (22%) of the study area. During 2000–2019, 4835 km^2 (15.8%) of forest within protected areas were classified as forest loss by the Hansen et al. (2013) dataset (Table 2). Côte d'Ivoire had the largest protected area network within the pygmy hippopotamus distribution (24 636 km^2) and accounted for the largest area of forest loss within protected areas (3809 km^2; Table 2). When the normalized area was considered, Liberia had lost the most forest (33.7%), followed by Côte d'Ivoire (15.5%), whereas Guinea and Sierra Leone had lost the least both in net surface area and in proportion of their protected areas (Fig. 4 & Table 2). Forest loss inside protected areas mainly occurred in northern, southern and western Côte d'Ivoire, as opposed to eastern and central protected areas within the study area. In Liberia, western protected areas were the most affected (Fig. 4).

'Shifting agriculture' was the main driver of forest loss inside protected areas across all countries, but especially in Côte d'Ivoire and Liberia, which accounted for 94% (4568 km^2) of total forest lost. 'Urban expansion' was the second largest driver of forest loss and represented c. 5% (254 km^2) of all forest lost inside protected areas. 'Intensive agriculture' represented <1% (13 km^2) of deforestation caused inside protected areas (Fig. 4 & Table 2).

Discussion

'Shifting agriculture' was the dominant driver of deforestation within the pygmy hippopotamus range across all countries and

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Table 1. Net and normalized areas of forest loss per country (km^2) between 2000 and 2019. Net area of forest loss refers to the area of forest with >50% canopy cover. Normalized area of forest loss is defined as the ratio between the net area of forest loss (km^2) and the area within the pygmy hippopotamus distribution (km^2) × 100. Total area of forest loss attributed to each driver (per country; km^2) is shown.

	Area within the pygmy hippopotamus distribution	Net area of forest loss	Normalized area of forest loss	Intensive agriculture	Urban expansion	Shifting agriculture
Côte d'Ivoire	79 917 km^2 (57.0%)	9825 km^2 (61.8%)	12.3%	102 km^2 (0.6%)	704 km^2 (4.4%)	9019 km^2 (56.7%)
Liberia	53 155 km^2 (37.9%)	5123 km^2 (32.2%)	9.6%	40 km^2 (0.3%)	142 km^2 (0.9%)	4941 km^2 (31.1%)
Sierra Leone	4814 km^2 (3.4%)	765 km^2 (4.8%)	15.9%	~1 km^2 (<0.1%)	26 km^2 (0.2%)	738 km^2 (4.6%)
Guinea	2335 km^2 (1.7%)	188 km^2 (1.2%)	8.0%	~1 km^2 (<0.1%)	17 km^2 (0.1%)	170 km^2 (1.0%)
Total	*140 221 km^2*	*15 901 km^2*		*144 km^2 (1.0%)*	*889 km^2 (5.6%)*	*14 868 km^2 (93.4%)*

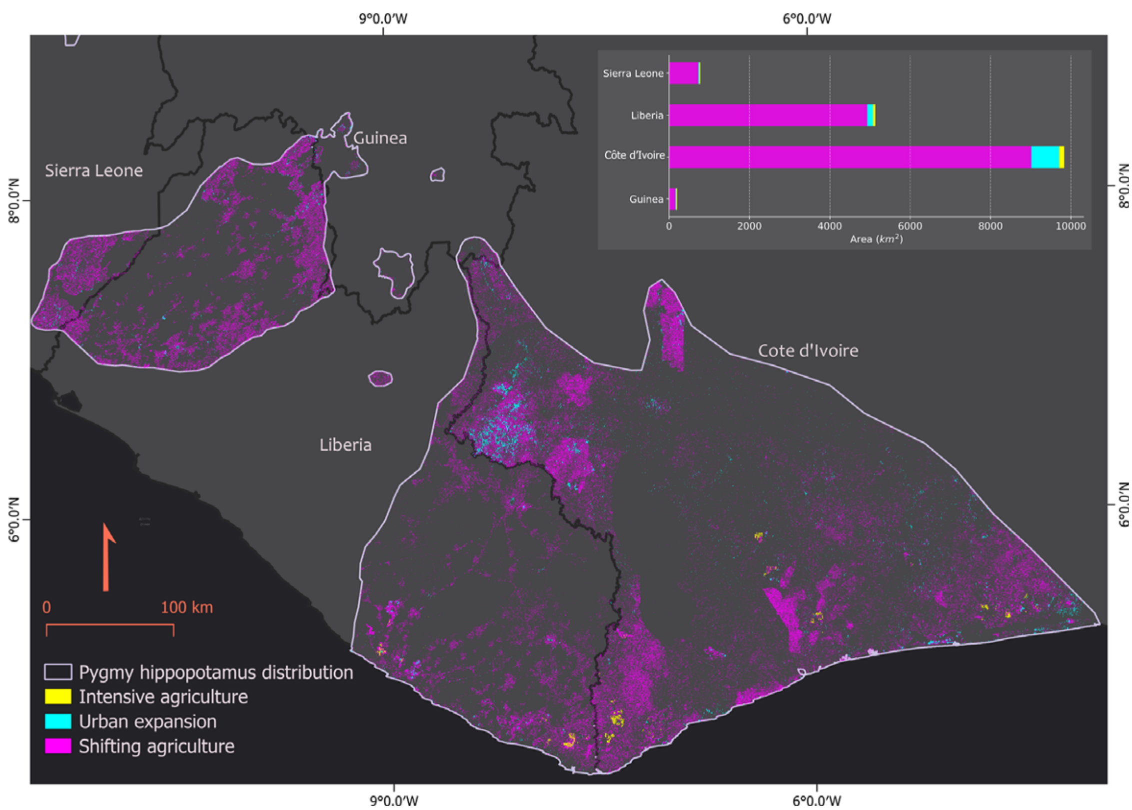

Figure 3. Distribution of drivers of forest loss in the study area during 2000–2019. The bar chart shows the area (km^2) of forest loss by driver per country (for display purposes smaller patches of the pygmy hippopotamus distribution located in Sierra Leone are omitted).

inside protected areas. Shifting agriculture has been identified as the major driver of deforestation in tropical African forests; however, recent estimates by country are limited (DeFries et al. 2010, Fisher 2010, Hosonuma et al. 2012, Bodart et al. 2013, Giam 2017, Curtis et al. 2018, Simmons et al. 2018). While Hosonuma et al. (2012) state that deforestation in Africa is driven by subsistence agriculture (c. 40%) and industrial agriculture (35%), our study found that the class 'Urban expansion' plays a more significant role than 'Industrial agriculture'. In West African countries, where forest cover is high and economic development is low, employment, food and energy demands are met by clearing forest for different activities (Leblois et al. 2017). Human population density and growth are thus ultimate drivers of deforestation (DeFries et al. 2010).

The human population in the four countries has increased 307% over the past 70 years, which translates into more demand for land to supply food and natural resources (United Nations 2019, World Bank 2019). These patterns of deforestation caused by subsistence and shifting agriculture are more evident in developing than developed countries (McDowell et al. 2020), and, once forests are cleared for shifting agriculture activities, less work is required to further transform these areas into industrial agriculture or urban centres (Bren d'Amour et al. 2017). More research into how drivers of forest loss have changed over the past decades, informed by the historical empirical record from satellite imagery, is needed to investigate how best to manage human impacts on the remaining forests in West Africa and the species that inhabit them.

West Africa has been forecast as a major centre of rapid human population growth (Seto et al. 2012). Although 'Urban expansion' was not the most important driver of forest loss in our study area, rapid population growth will probably involve further deforestation, even in protected areas (Fig. 4). According to Bogui et al. (2016), increasing human presence close to remaining forests is likely to reduce pygmy hippopotamus populations, with human–wildlife conflict expected to increase as some hippopotami venture into farmland and plantations to find food (Robinson 1970,

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Table 2. Net and normalized areas of forest loss inside protected areas per country (km^2) between 2000 and 2019. Net area of forest loss refers to the area of forest with >50% canopy cover. Normalized area of forest loss is defined as the ratio between the area of forest loss within protected areas (km^2) and total protected area within pygmy hippopotamus distribution (km^2) × 100. Areas of drivers of forest loss inside protected areas partially or totally within the pygmy hippopotamus distribution (per country; km^2) are shown.

	Total protected area within pygmy hippopotamus distribution	Area of forest loss within protected areas	Normalized area of forest loss	Intensive agriculture	Urban expansion	Shifting agriculture
Côte d'Ivoire	24 636 km^2 (80.3%)	3809 km^2 (78.8%)	15.5%	10 km^2 (0.6%)	172 km^2 (4.4%)	3627 km^2 (56.7%)
Liberia	2548 km^2 (8.3%)	858 km^2 (17.7%)	33.7%	~1 km^2 (0.3%)	66 km^2 (0.9%)	791 km^2 (31.1%)
Sierra Leone	1761 km^2 (5.7%)	29 km^2 (0.6%)	1.6%	~1 km^2 (<0.1%)	1 km^2 (0.2%)	27 km^2 (4.6%)
Guinea	1724 km^2 (5.6%)	139 km^2 (2.9%)	8.1%	~1 km^2 (<0.1%)	15 km^2 (0.1%)	123 km^2 (1.1%)
Total	*30 669 km^2*	*4835 km^2*		*13 km^2 (1.0%)*	*254 km^2 (5.6%)*	*4568 km^2 (93.5%)*

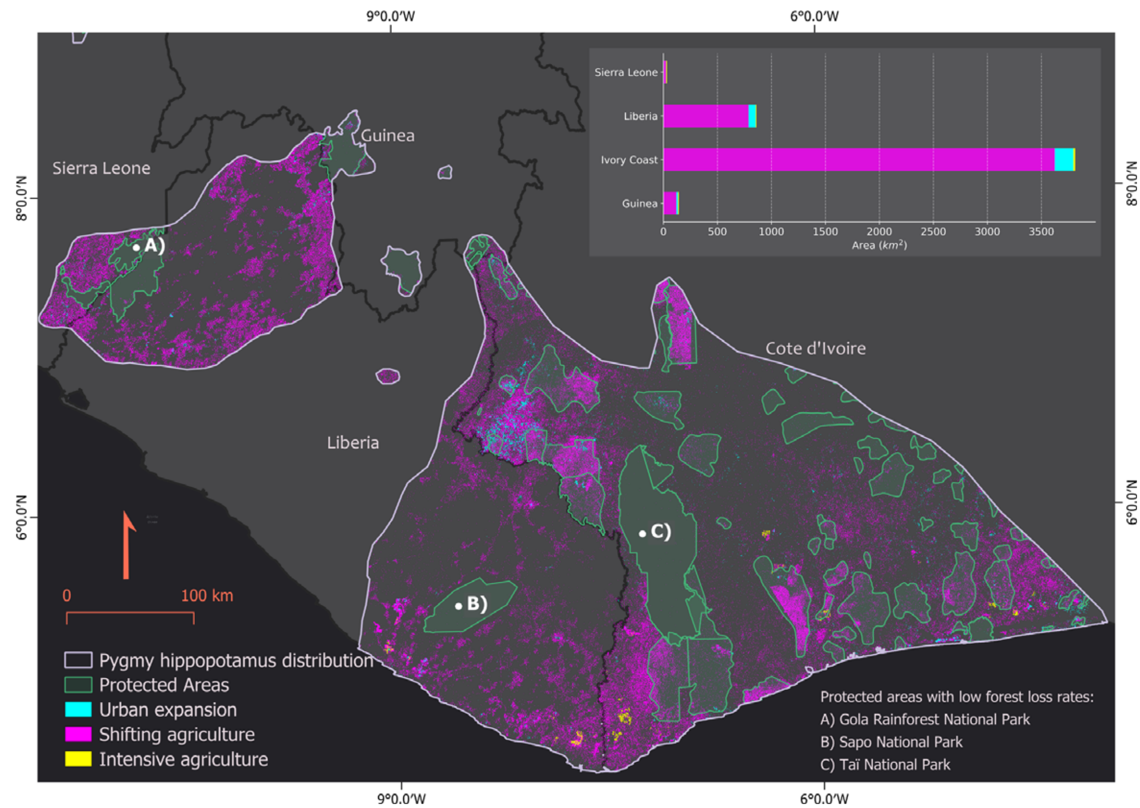

Figure 4. Distribution of drivers of forest loss within protected areas in the study area during 2000–2019. The bar chart shows the area (km^2) of forest loss by driver inside the protected areas of each country (smaller patches of the pygmy hippopotamus distribution located in Sierra Leone are omitted).

Bülow 1987, Hentschel 1990, Conway 2013). Further investigation is needed to better understand human–wildlife interactions (Conway et al. 2015, Robinson et al. 2017) and the proximate drivers of pygmy hippopotamus habitat quality across the UGF region.

Our results are consistent with Curtis et al. (2018), who reported 13% forest loss in Africa, and Global Forest Watch (Hansen et al. 2013), where Côte d'Ivoire, Liberia, Sierra Leone and Guinea have lost 26%, 5.9%, 11% and 6.6% of humid primary forest since 2002, respectively, meaning that the UGF has been heavily exploited in the past two decades (Table S3). Our results indicate that industrial agriculture in the study area corresponds mainly to oil palm, tea and cocoa; however, cocoa plantations are common across West Africa, with Côte d'Ivoire producing 40–50% of the world's cocoa (Smith Dumont et al. 2014, Wessel & Quist-Wessel 2015).

Côte d'Ivoire and Ghana have the largest areas of oil palm plantations in Africa (200 000 and 100 000 ha planted, respectively) and are the largest exporters of palm oil in the UGF region (Descals et al. 2021, FAO 2021). Plantations of oil palm in Côte d'Ivoire and Ghana increased by c. 60% between 1989 and 2013 (Vijay et al. 2016), and the world's demand for palm oil is expected to grow threefold by 2050 from 2000 levels (The Economist 2014). West African countries, including Liberia and Côte d'Ivoire, are expected to increase their production to meet this demand. Despite this, Vijay et al. (2016) suggest that the increased area of these plantations may not be linked to deforestation but to conversion of previously deforested areas. This claim, however, cannot be verified without official figures of deforestation and oil palm plantations or via independently conducted studies of deforestation and land-change dynamics across the region. Our results suggest that although oil palm contributes to considerable forest loss in the UGF, it has been primarily concentrated in southern Côte d'Ivoire. If Vijay et al. (2016) are correct, only negligible new forest loss should occur due to industrial agriculture expansion in the coming years, potentially reducing the pressure on the remaining forest. Despite this, it is crucial to further

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understand how the pygmy hippopotamus and other threatened species use different ecosystems in the region to improve understanding of the impacts of various forest-loss drivers on threatened species.

A classification model that includes more drivers of forest loss (i.e., individual crops, fire) could improve conservation efforts (e.g., targeted policies and resources) by allowing decision-makers to understand not only the location of forest loss but also the frequency and intensity of the activities that drive deforestation, as well as to effectively monitor and evaluate the impacts of their policies, interventions and programmes. The high prevalence of clouds in the region and the spectral similarity of forests and plantations often lead to driver misclassification (e.g., see Curtis et al. 2018). These two limitations could be addressed with Earth observation data obtained from a variety of recently launched sensors that have improved temporal and spatial resolution. However, acquiring these data can be costly, and their use is likely to involve a number of trade-offs, such as reduced spectral resolution compared to Landsat and Sentinel-2 sensors, which may limit their ability to generate the diverse covariates necessary for a pixel classification approach such as that developed in our study. Our study therefore represents a first step to understanding how land cover is changing in the UGF and will help inform conservation efforts in it.

Forest loss inside protected areas

Almost 16% of the forest with ≥50% canopy cover inside protected areas was lost between 2000 and 2019, with 'Shifting agriculture' being the main driver of deforestation. The magnitude is this driver is 10-fold greater than the second most significant driver of deforestation, 'Urban expansion', inside the protected areas of all countries analysed here. Despite some methodological differences, our results align with those of Spracklen et al. (2015), who found that Côte d'Ivoire had some of the highest rates of deforestation inside and within 10 km of protected areas (0.5% year^{-1}) in West Africa between 2000 and 2012.

Our findings suggest that forest loss inside Taï (Côte d'Ivoire), Gola Rainforest (western Liberia) and Sapo (eastern Liberia) national parks is negligible and unrelated to the identified drivers assessed, which is not the case for other protected areas in the region. Taï, Gola Rainforest and Sapo national parks host several pygmy hippopotami populations (Bogui et al. 2016); therefore, these results are encouraging. There is, however, large-scale fragmentation alongside the western border of Taï National Park related to timber extraction and the establishment of new crops (Chatelain et al. 2010). According to Chatelain et al. (2010), the remaining patches of forest to the west of Taï were expected to disappear, driven by land clearing for the expansion of cropland and existing settlements, and our results suggest that 'Shifting agriculture' activities are increasing in the area, but they are more prominent to the north-west and south-west of the National Park (Fig. 4).

Our results provide regional support for agricultural expansion and 'Urban expansion' being unambiguously linked to forest loss inside protected areas globally (Heino et al. 2015). Protected areas in West African countries are generally less effective at preventing forest loss than in other regions, with deforestation often occurring both outside and inside protected areas (Leberger et al 2020). We have demonstrated that protected areas within the pygmy hippopotamus's range are affected by forest loss, and this may lead to human–wildlife conflicts.

Implications for conservation of the pygmy hippopotamus

We provide evidence that pygmy hippopotamus populations are and will continue be threatened by the expansion of shifting agriculture, grazing and human settlements. By identifying the proximate drivers of forest loss, we understand better the risk of extinction to the pygmy hippopotamus and other species in the UGF (Chatelain et al. 2010). Our results indicate that Taï, Gola Rainforest and Sapo national parks account for 25% of the protected habitat in the pygmy hippopotamus distribution but only for 2% of the deforestation inside protected areas. In other words, these three protected areas provide almost all of the intact habitat for pygmy hippopotami and therefore should be given high priority for conservation. Importantly, these protected areas are spatially distributed across the region, hence ensuring the conservation of populations with different genetic pools. These protected areas present excellent sites to assess the demography, viability and extinction risk of pygmy hippopotamus populations as well as the effects of changing climate and forest loss on this species. The spatially explicit distribution of deforestation drivers presented here can inform conservation actions aimed at reducing forest loss while maintaining the remaining forests in the region. Critically, the reduction of agriculture and grazing activities inside and close to protected areas must be prioritized in Côte d'Ivoire and Liberia.

Conclusion

Our spatially explicit classification of deforestation drivers in the pygmy hippopotamus distribution area using the Sentinel-2 image archive and a random forest model shows that habitat loss primarily by 'Shifting agriculture' but also by 'Urban expansion' is pervasive. The protected areas in the UGF may not be fulfilling their role in providing pygmy hippopotami with protection from forest loss; therefore, it is imperative to prioritize conservation efforts in areas where deforestation is low (e.g., Taï, Sapo and Gola Rainforest national parks) and to assess the viability of pygmy hippopotamus populations in those areas.

Supplementary materials. For supplementary material accompanying this paper visit https://doi.org/10.1017/S0376892923000310.

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Ethical standards. None.

Data sharing. Google Earth Engine code for the analyses are accessible through Zenodo: https://doi.org/10.5281/zenodo.7091804 (Erazo Mera, Younes Cárdenas, Murray, 2022). All Sentinel-2 imagery is publicly available via Sentinel Hub: https://sentinel.esa.int/web/sentinel/sentinel-data-access or through Google Earth Engine.

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