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Identifying areas where biodiversity is at risk from potential cocoa expansion in the Congo Basin

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ABSTRACT

The growing global demand for cocoa is leading to large-scale land-use changes and habitat loss in biodiversity rich areas such as the tropical lowland forests of Africa. Low productivity and climate change are projected to affect cocoa production in major parts of West Africa, where most of the world's cocoa is produced. Such effects are expected to drive expansion into Central Africa where governments are looking towards commodity crop production, including cocoa, to support economic development objectives. For example, Cameroon is the fifth largest cocoa producer in the world and aims to triple its cocoa production volume by 2030. A tripling in yields is unlikely, especially within that timeframe, meaning this will only be possible through expansion. In conflict with this trajectory is new legislation in the UK and the EU, banning the import of commodities linked to deforestation. Cocoa is the fastest expanding export crop in Sub-Saharan Africa, but little is known about potential expansion areas in the Congo Basin and how this will impact biodiversity. In this study, we attempt to address this gap by answering two questions: (i) Where are available suitable areas to grow cocoa in the Congo Basin? (ii) Where are the likely impacts of cocoa expansion on biodiversity? We followed a spatial exclusionary approach to identify available areas for cocoa cultivation within areas with moderate to high climatic suitability for cocoa. This was achieved by identifying and excluding land-use and land cover types that are unsuitable for cocoa expansion under different assumptions. We then identified areas of high risk within the available area for cocoa as those with high cocoa suitability and high biodiversity significance (i.e., rarity-weighted species richness) and high accessibility. The study highlights the Congo Basin's central belt as an area where biodiversity would be put at high risk from cocoa expansion. Even with an effective no deforestation policy, biodiversity loss remains a concern in agricultural areas like western Cameroon and the northeastern and eastern edges of the Democratic Republic of the Congo. This research provides valuable insights that can be used to guide the development of strategies that mitigate the adverse effects of cocoa expansion on biodiversity.

1. Introduction

1.1. The Congo Basin and deforestation

The Congo Basin (Cameroon, Gabon, Republic of Congo, Democratic Republic of the Congo (DRC), Central African Republic, and Equatorial Guinea) hosts 1.8 million ha of primary forest, making it the largest tropical forest in the world after the Amazon (Mayaux and Malingreau, 2000). It hosts 70 percent of Africa's forests and a large diversity of flora and fauna, with many endemics. DRC has vast tracts of peatland that are estimated to store as much carbon as all the tropical forests in the Congo Basin (Dalimier et al., 2022; Dargie et al., 2017). The Congo Basin forests are also economically important, as more than 75 million people depend on them for their livelihoods (Bele et al., 2015; Megevand, 2013; Tegegne et al., 2016).

Historically, deforestation in the region has been relatively low (Megevand, 2013). However, the area is under increasing pressure from a variety of sources, of which forest clearing for agriculture is the

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primary threat (Norris et al., 2010). Ernst et al. (2013) estimated that the annual rate of net deforestation in the Congo Basin increased from 0.09 % to 0.17 % between 1990 and 2005. Vancutsem et al. (2021) found that 30–40 % of tropical moist forests in the region were degraded in 2019. Most forest clearing in the Congo Basin is done by smallholder farmers, both for subsistence and commercial crop farming (Molinario et al., 2020; Tyukavina et al., 2018). Large scale clearing for agro-industrial plantations was rare until relatively recently (Feintrenie, 2014; Ordway et al., 2017).

Globally, there is increasing concern about the role of cocoa and other widely traded commodities in driving deforestation. This is reflected in a suite of commitments to end deforestation in agricultural supply chains by governments and the private sector from 2015 onwards (Carodenuto, 2019), including within the cocoa sector. Public-private initiatives such as the Cocoa Forest Initiatives (CFI) in Ghana and Côte d'Ivoire and Roadmap to Deforestation Free Cocoa in Cameroon aim to support the prevention of further deforestation and the restoration of degraded forests, while supporting increased cocoa production in alignment with national REDD+ strategies and other relevant national policies and strategies. The recently adopted EU regulation on deforestation-free supply chains aims to minimise the import of products associated with deforestation or forest degradation, including cocoa (European Union, 2023). By prohibiting the import of commodities associated with any deforestation after 31 December 2020, this legislation goes beyond more recent UK (UK Public General Acts, 2021) and US bills (United States Congress, 2021), which only ban commodities associated with illegal deforestation in the producer country.

1.2. Current state and potential future of cocoa cultivation in the Congo Basin

Global demand for cocoa is expected to increase, especially from Asia (Li and Mo, 2016) which is anticipated to become an important driver of deforestation in cocoa producing regions such as the Congo Basin (Clough et al., 2009; De Beule et al., 2014). Cocoa has expanded more rapidly than other export crops in sub-Saharan Africa since the 1980s (Ordway et al., 2017). This expansion could lead to an estimated loss of up to 40,000 ha of forests in this decade (De Beule et al., 2014). In Cameroon, the third largest cocoa producer in Africa (ICCO, 2017) and fifth in the world, cocoa production more than doubled between 2002 and 2017, reaching 295,000 tonnes (FAO,2020). This increase was mainly due to the expansion of harvested area, which also doubled in the same period (FAO, 2020). Average cocoa yields increased only slightly and remain low with current averages around 400 kg/ha (Saj et al., 2017; Wessel and Quist-Wessel, 2015). Furthermore, Cameroon aims to triple national production volumes by 2030 (Lescuyer and Bassanaga, 2021; MINEPAT., 2020). It is unlikely yields will triple by 2030, which means meeting this objective may lead to increased pressure on natural lands such as forests. In Cameroon, cocoa is traditionally grown mainly in the central-southern region. However, it is increasingly expanding into the forest-savanna transition zone. DRC produces only small amounts of cocoa, mainly in North Kivu, though production was higher during the colonial era and mainly located in the western part of the country, where it is expected to expand in the future (De Beule et al., 2014). With its fertile soils, DRC is considered to have high potential for future cocoa expansion, but the implications for biodiversity are understudied.

Climate change is expected to reduce the suitability of land for cocoa production in parts of West Africa, where most of the world's cocoa is produced (Schroth et al., 2016). Declining yields in West Africa (due to management and climate factors) are expected to lead to a shift in production area into the forested and savanna areas of Cameroon and further east to other Congo Basin countries, where suitability will likely remain high or increase (De Beule et al., 2014; Läderach et al., 2013). This will compound existing trends of commodity crop expansion in the Congo Basin (Ordway et al., 2017).

1.3. (Potential) impacts of cocoa growing on biodiversity in the Congo Basin

Cocoa-driven deforestation is characterised by a boom and crisis cycle, historically associated with migration of people seeking land and labour (Ruf and Schroth, 2004). After about 30 years, impoverished soils, pest and disease pressures make it economically more advantageous to plant on cleared forest land rather than rejuvenating existing plantations (Gockowski and Sonwa, 2011; Ruf et al., 2015). As cocoa plantations are established under the often progressively thinned canopy of degraded or intact forest, this results in a loss of forest tree species as well as habitat for other organisms (De Beenhouwer et al., 2013; Maney et al., 2022; Tondoh et al., 2015).

Given projected increased global demand, regional policy objectives to boost production and uncertainty about the future climatic suitability of cocoa production in West Africa, cocoa production is likely to expand in the Congo Basin. Against this background, and considering the global biodiversity importance of the region, we aimed to address the following two questions: (i) Where are the available suitable areas to grow cocoa in the Congo Basin? (ii) Where are the areas where biodiversity is at risk due to potential cocoa expansion? We explore these questions in two cases. In the first case, cocoa expansion is constrained by existing biophysical and (assumed) legal barriers. In the second case, in addition to these biophysical and legal barriers, all forest areas are excluded to reflect the requirements of the EU regulation on imported deforestation.

2. Material and methods

In this study, we defined 'available area for cocoa' as the land area that is potentially available for cocoa cultivation after excluding areas where cocoa cannot be cultivated due to physical or legal barriers (see Table 2). We defined 'available suitable area for cocoa' as the potentially available area for cocoa that has the suitable climatic conditions for cocoa cultivation. This includes areas where cocoa is currently grown, though we cannot separate these out as maps of areas of cocoa cultivation are not available for the region.

To map the available suitable area for cocoa cultivation, we used an exclusionary approach, where we identified and excluded land use types where we assume cocoa cannot expand (Table 2, Fig. 1). We assumed that physical and/or legal barriers preclude these areas from being converted to cocoa and that no cocoa is currently grown there. These layers were then erased from a cocoa climatic suitability layer, which is a modelled global distribution of climatic suitability for cocoa cultivation.

2.1. Climatic suitability for cocoa production

We modelled the global distribution of suitable climates for cocoa production under current climate conditions. A database of cocoa occurrence locations, a random sample to characterise the general environment and interpolated climate data from WorldClim 2.0 (Fick and Hijmans, 2017) were used to train the Random Forest (RF) classification algorithm. RF are machine learning classifiers that are formed by ensembles of classification trees (Breiman, 2001). The trained classifier was applied to the climate layers and provided a probability for whether a pixel cell was similar to the climate at known cocoa locations on a scale from zero to one. Below, we detail the steps we followed in modelling the climatic suitability for cocoa production.

We assembled a global dataset of cocoa occurrences with the objective to include all major climatic regions where cocoa is produced. Data was collected from stakeholders such as private sector actors, research institutions, certification programmes in West Africa, Asia, and South and Central America. We also used data from previous publications on the climate change impacts in West Africa (Läderach et al., 2013; Schroth et al., 2016), GBIF (Global Biodiversity Information Facility) (Global Biodiversity Information Facility (GBIF, 2015)) and

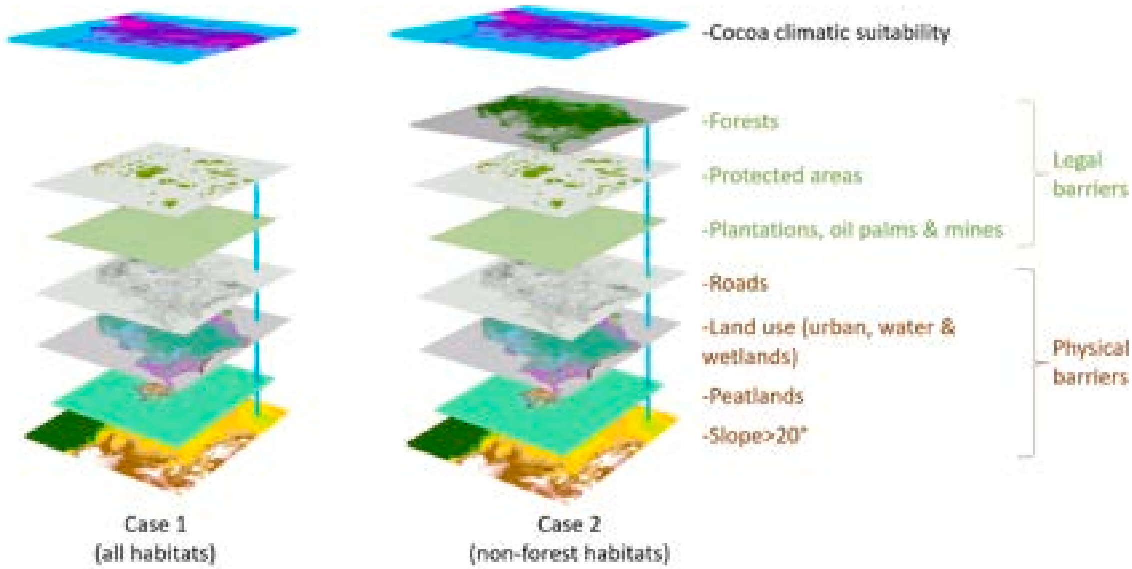

Fig. 1. Layers used to produce the available suitable area for cocoa expansion (data sources for layers in Table 2).

centroids of census units of Peru in which relevant cocoa quantities were reported (Instituto Nacional De Estadistica E Informatica, 2013). The resulting raw database included 96,181 cocoa occurrence locations from 60 countries. We reduced this initial dataset to unique occurrence pixels at 10 Arcmin (about 20 km at the equator) because this has been shown to eliminate bias from highly clustered occurrences (Boria et al., 2014). We further excluded unfeasible locations which had average minimum temperature <10 °C and locations that require irrigation because annual total precipitation was <900 mm/year. The final database included 3, 103 cocoa occurrence locations across 52 countries.

For climate conditions (1950–2000), we used the WorldClim dataset (Version 2.1) at 10 arc-minute resolution (Fick and Hijmans, 2017). WorldClim provides data on monthly precipitation, mean monthly minimum and maximum temperatures, and 19 bioclimatic variables derived from this data. To the commonly used set of 19 bioclimatic variables, we added variables that directly relate to cocoa cultivation. We added as variables the number of consecutive months with less than 100 mm of precipitation, the number of consecutive arid months (precipitation lower than potential evapotranspiration (PET)), the total water deficit during this period, growing season average temperatures and mean dry season maximum temperatures. Potential evapotranspiration is considered a good proxy of vapour pressure (Allen et al., 1998) which may have direct effects on the cocoa tree (Mielke et al., 2005). We estimated potential evapotranspiration following the modified Hargreaves approach as recommended by the FAO (Allen et al., 1998). This resulted in 33 bioclimatic variables. To reduce multicollinearity, we removed variables from the climate data with absolute pair-wise Pearson correlation coefficients greater than 0.8 (Dormann et al., 2013). The final set of bioclimatic variables for suitability modelling included 12 variables (Table 1).

We used the RF (Breiman, 2001) classifier in two distinct applications: (1) We initially used it to produce a dissimilarity measure to group occurrence locations into agro-climatic clusters with similar climate characteristics in an unsupervised variation. (2) We used the RF classifier to classify climate data of current conditions into the resulting agro-climatic zones. We used the randomForest package (Liaw and Wiener, 2002) in the statistical software R (R. Core Team, 2021) that implements the RF approach. First, to reduce climatic bias in the occurrence sample, we clustered the occurrences in distinct agro-climatic zones for cocoa. We used the RF classifier in unsupervised mode (Shi and Horvath, 2006) to calculate dissimilarities based on the bioclimatic variables at cocoa locations and determined the number of clusters based on visual inspection of a cluster dendrogram. Second, to train the RF classifier to recognize suitable climates, we extracted the values of the 12 selected climate variables using the geolocation data of the cocoa occurrences. From each agro-climatic zone, an equally sized sample was drawn. In addition, a random background sample set of points, not known to produce cocoa, was created to characterise the general environment at a sampling ratio of 1:1 background to occurrence locations. Each RF classifier was configured to create 100 decision trees, and to be replicated 25 times (‘forests’). In each repeat, a different subset from the occurrence sample was drawn at the size equalling half the number of cases in the smallest subgroup. Such reduction of ecological sampling bias has been shown to improve the capacity of niche based approaches to correctly predict species distributions (Varela et al., 2014). From this subset, we used 80 % for training, and 20 % for evaluation. The suitability distribution was validated using the multiclass area under receiver operating characteristic curve (AUC) (Hand and Till, 2001) as implemented in the R package “pROC” (Robin et al., 2011).

Table 1
The bioclimatic variables used for the cocoa suitability modelling.

Bioclimatic variable	Description
BIO 1	Annual Mean Temperature
BIO 4	Temperature Seasonality (standard deviation *100)
BIO 7	Temperature Annual Range (BIO5-BIO6)
BIO 15	Precipitation Seasonality (Coefficient of Variation)
BIO 16	Precipitation of Wettest Quarter
BIO 18	Precipitation of Warmest Quarter
BIO 19	Precipitation of Coldest Quarter
BIO 20	Number of Consecutive Months < 100 mm precipitation
BIO 22	Sum of water deficit during dry season
BIO 26	PET seasonality (Coefficient of Variation)
BIO 30	PET of wettest quarter
BIO 33	PET of coldest quarter

2.2. Available suitable area for cocoa production

In our analysis, we only considered areas with climatic suitability greater than 0.25 (i.e., moderate to high climatic suitability). The rationale behind using a cutoff value above 0.25 was to exclude areas where cocoa is most likely not suitable to grow. All existing cocoa sites from our dataset in the Congo Basin were in areas greater than 0.4 suitability value and <0.1 % of existing cocoa sites globally from our dataset had <0.25 suitability values. The alignment of this threshold of 0.25 with the global cocoa suitability patterns supports its validity in identifying suitable regions within the Congo Basin. Some of these suitable areas likely already have cocoa indicating that there could be potential for further intensification in these areas. Intensification is defined here as an increase in yields in existing cocoa farms. This could occur by increasing cocoa yields inno or low shade systems or by increasing cocoa productivity in shaded agroforestry systems.

Two cases were then analysed at 1 km resolution (see Table 2 for the list of data layers that were excluded in each case). In the first case, all assumed physical barriers and areas allocated to other land uses (protected areas, concessions, etc) were excluded. We assume that in forest areas that are already allocated to other agricultural or other land uses, such as tree plantation, oil palm, mining or logging concessions, the likelihood of conversion to cocoa is smaller than in non-allocated forests. Whether these areas are really precluded from cocoa growing may vary on the ground and needs to be confirmed. In the second case, in addition to the layers excluded in case one, forest layers (open and closed forests > 15 % tree canopy cover) were also excluded to reflect the requirements of the EU regulation on imported deforestation. Under the EU regulation, forest is defined as "*land spanning at least 0.5 ha, with trees higher than 5 m and a canopy cover of at least 10 %. Specifically excluded are agricultural plantations and land that is predominantly under agricultural or urban land use*" (https://www.iisd.org/articles/policy-analysis/deforestation-overview-eu-british-proposals).

All layers were clipped to the study area, converted to raster and then resampled to 1 km resolution. Finally, the layers were erased from the base cocoa suitability layer using raster calculator on ArcGIS Pro 2.8. This generated the available suitable area for cocoa expansion/intensification.

Table 2
Spatial layers that were used to produce the available suitable area for cocoa expansion. *Forests were excluded only from case 2 (i.e., the policy enacted case).

Layer	Data source	Reason for exclusion	Case 1	Case 2
Slope (>20°)	(Yamazaki et al., 2017)	Physical barrier (>20° was chosen as the suitable slope for cocoa production due to low suitability in the range of 10°–30° and unsuitability above 30° (Hanson et al., 1998))	X	X
Peatlands (palm-dominated swamp and hardwood swamp with likelihood probability >=0.5)	(Dargie et al., 2017)	Physical barrier	X	X
Waterbodies	Copernicus 2019 landcover data (Buchhorn et al., 2020)	Physical barrier	X	X
Herbaceous wetlands	Copernicus 2019 landcover data (Buchhorn et al., 2020)	Physical barrier	X	X
Urban areas	Copernicus 2019 landcover data (Buchhorn et al., 2020)	Physical barrier	X	X
Road density (major road, minor road and tracks)	(Theobald et al., 2020)	Physical barrier	X	X
Mining areas	(Maus et al., 2020)	Legal barrier	X	X
Oil palm plantations	(Descals et al., 2021)	Legal barrier	X	X
Plantations	(Harris et al., 2019) Global Forest Watch tree plantations	Legal barrier	X	X
Protected areas	(UNEP-WCMC & IUCN, 2021)	Legal barrier	X	X
Forests* (open and closed forests > 15 % tree canopy cover)	Copernicus 2019 landcover data (Buchhorn et al., 2020)	Legal barrier		X

2.3. Accessibility of area potentially available and suitable for cocoa

In sub-Saharan Africa, shorter travel time to the nearest large city is associated with higher crop production (Dorosh et al., 2012). Therefore, areas of high cocoa suitability and high accessibility to the nearest large city are likely the first areas where cocoa expansion and intensification will take place.

To determine high accessibility, we used a global accessibility layer (Weiss et al., 2018) that measures the travel time to the nearest major city in 2015 with a population of at least 50,000. The raster values were inverted to make higher values indicate a higher accessibility (i.e., less time needed to travel to the nearest large city). We then produced bivariate maps in RStudio v2021.09.0 (R Core Team, 2021) using the accessibility layer and the cocoa suitability layers that we generated in the previous step.

2.4. Areas of potential risks to biodiversity

We identified areas combining high cocoa suitability, high biodiversity significance and high accessibility as priority areas in terms of potential biodiversity risk. To represent areas of importance for biodiversity, we used a metric called rarity weighted richness (RWR), which we refer to as biodiversity significance.

We prepared this map following the approach of Sassen et al. (2022) and area of habitat (AOH) following Jung et al. (2020). We used range data from the IUCN Red List (IUCN, 2019) for all mammals, amphibians and birds and refined these based on species-specific altitudinal limits and habitat preferences. For each species, these preferences were applied to elevation (Danielson and Gesch, 2011) and habitat (Jung et al., 2020) datasets, to select only areas of suitable elevation and habitat within 1 km pixels. A proportional approach was used for the habitat within each pixel, hence habitats that are under 1 km resolution were included. This resulted in AOH maps (Brooks et al., 2019) for each species. For each AOH map, we weighted pixels by the area of habitat in that pixel divided by the total global area of habitat for that species. These maps were summed together to create a single rarity-weighted richness map for the Congo Basin. We used Google Earth Engine (Gorelick et al., 2017) for all AOH refinement and the creation of the final RWR map, using a combination of the Python API and the JavaScript Code Editor.

Finally, we combined this biodiversity significance layer with the cocoa suitability and availability layers generated in the previous steps into single multi-dimensional red-green-blue (RGB) plots for both the considered cases.

3. Results

3.1. Available suitable area for cocoa production

By extrapolation of the trained RF classifier on climate layers, we obtained a map of suitability for cocoa production. This suitability score was based on the number of trees across all forests that cast a vote for a cocoa climate zone. Thus, the score can be interpreted as a measure of similarity of the climate at a grid cell to climate at known cocoa occurrence locations. The average AUC over all classifiers (.96) showed a good capacity of the classifier to differentiate the suitable agro-climatic zones for cocoa.

All countries in the Congo Basin have areas that are suitable but unavailable for cocoa growing (Fig. 2.A). Northern parts of Cameroon and the Central African Republic, southern parts of DRC, southern Congo, and southern Gabon, are hardly or not climatically suitable for cocoa, regardless of legal or biophysical barriers. In contrast, southern parts of Cameroon, most of Equatorial Guinea (including parts of central and northern Bioko islands), northern parts of Gabon and part of central and eastern DRC were found to be highly climatically suitable for cocoa.

When forest layers (open and closed forests) are excluded from the analysis (Fig. 2.B), much of the suitable available area found in Fig. 2.A disappears, such as the southern parts of Cameroon, most of Equatorial Guinea, parts of Gabon and most of central and eastern DRC. Similarly, only small parts of central Cameroon and eastern DRC were found to have highly suitable areas available for cocoa outside forests.

3.2. Accessibility of area potentially available and suitable for cocoa

Areas with high cocoa suitability and high accessibility are likely to be the places where cocoa is already grown and intensification could take place, or where expansion would happen first. These include central and southwest Cameroon, most regions in Equatorial Guinea (including parts of central and northern Bioko islands), western edge of Central African Republic, small areas in north-western Gabon, northeastern and eastern edges of DRC and parts of southwest Congo (Fig. 3.A). These areas are both highly suitable for cocoa and easily accessible from a major city.

When forest areas are removed, scattered areas that are suitable, available and easily accessible remain, along with a slightly larger area in southwest DRC (black areas in Fig. 3.B). These southwestern areas predominantly consist of herbaceous vegetation.

3.3. Areas of potential risks to biodiversity

Areas of high cocoa suitability and high biodiversity significance represent a high potential risk for biodiversity. The highest potential risk areas in this regard are south and west Cameroon, most of Equatorial Guinea, parts of north and northwest Gabon, parts of north and northwest Congo and large areas in north and central DRC (Fig. 4.A). Some of the areas that are potentially at risk due to a combination of high cocoa suitability and high biodiversity significance are also highly accessible (light yellow/white pixels in Fig. 4.A1 and 4.A2). Such areas include southwestern and southern Cameroon, which are major cocoa-producing regions (Supplementary Figure A.1), as well as western, northeastern and central Equatorial Guinea, and northeastern and eastern edges of DRC (Fig. 4.A). Eastern DRC provinces Ituri, and North and South Kivu are also areas with Ebola risk as well as armed conflict (Supplementary Figure A.2).

When forest areas are removed, areas of high potential risk for biodiversity due to high suitability for cocoa growth include parts of west Cameroon, small, scattered parts of southeast Gabon and central Congo, northeast and eastern edges of DRC and parts of northwest DRC, and small scattered parts of southwest Central African Republic and Equatorial Guinea (Fig. 4.B). However, when considering both high suitability and accessibility, the areas that could be most at risk from biodiversity loss outside forests are mainly in west Cameroon (Fig. 4.B1) and northeastern and eastern edges of DRC (Fig. 4.B2), though there are other biodiversity risk areas outside of forests scattered across the region.

High biodiversity risk areas (with high biodiversity significance, cocoa suitability and accessibility) consist mostly of herbaceous vegetation (in the savanna-forest transition zone of western Cameroon, Fig. 4.B1), and temporary cropland areas (in northeastern and eastern edges of DRC, Fig. 4.B2).

4. Discussion

In this study, we used global open-source data to identify areas where cocoa cultivation could potentially expand or intensify in the Congo Basin based on suitability and land availability criteria. We then mapped potential biodiversity risk areas within these regions based on biodiversity importance and accessibility. This approach can be readily replicated for other commodities for which limited spatial data are available. It can also be conducted across different spatial scales.

4.1. Implications of findings

We identified areas where biodiversity is at risk due to potential cocoa expansion, primarily in central regions of the Congo Basin (a largely continuous/connected patch extending from western and southern Cameroon to northeastern and eastern DRC). There are several important protected areas surrounding these regions that host a large diversity of endemic and threatened species. Among these are Cameroon's Nki national park, DRC's Okapi Wildlife Reserve, Maiko National Park and the transboundary Virunga National Park (Figure A.2). These areas are also highly accessible, leading to pressure from agricultural expansion, including cocoa, that then combines with bushmeat hunting and illegal logging around the fringes of the parks (Laurance et al., 2014; Wilkie et al., 2000).

Some of these areas align with findings by de Beule et al. (2014), who estimated potential cocoa expansion and deforestation areas based on field visits and literature review. Examples include: i) Mambasa area – which mostly consists of Ituri forest and is close to Okapi Wildlife Reserve (up to 18,000 ha of deforestation), ii) Mbandaka area in the Equatorial province with water access routes through the Congo River (up to 12,000 ha of deforestation) iii) Beni area near Virunga national park (up to 8,250 ha of deforestation) (De Beule et al., 2014). To address these pressures, there are some initiatives that seek to support both local livelihoods and forest conservation, including by promoting cocoa as an alternative economic activity to bushmeat hunting and logging. For example, around the Okapi Wildlife reserve, the Sustainable Trade Initiative IDH works with the Wildlife Conservation Society (WCS) and private sector partners to support sustainable cocoa production around the reserve (CBI, 2023).

The suitable areas that remain after removing forest classes were mostly herbaceous vegetation. In Cameroon, cocoa production is promoted in the savanna transition zone to increase carbon sequestration and avoid deforestation (Government of Cameroon, 2021; Jagoret et al., 2012; Nijmeijer et al., 2019). This poses unclear implications for biodiversity and local people. Many existing cocoa-growing areas in the region were likely considered forests in the land cover dataset that we used due to the prevalence of shaded agroforestry systems. Diverse shaded cocoa has been shown to host significant biodiversity (Maney et al., 2022). In such instances, the main risk is not one from expansion, but from production systems being intensified through simplification leading to tree cover loss, i.e., moving towards low shade or monoculture systems. This is especially likely to happen in areas with better market access. For example, Sonwa et al. (2007) found that around Cameroon's capital city Yaoundé, agroforests were less diverse than in less urbanised sub-regions. They also contained a higher relative density of (exotic) food producing trees. In countries with much smaller cocoa-growing areas within still highly forested landscapes, expansion into primary forests is likely a greater risk.

Nearness to urban areas poses a risk factor for intensification and expansion of cocoa cultivation. Conversely, highly accessible areas (close to roads and large settlements) are likely to have lower

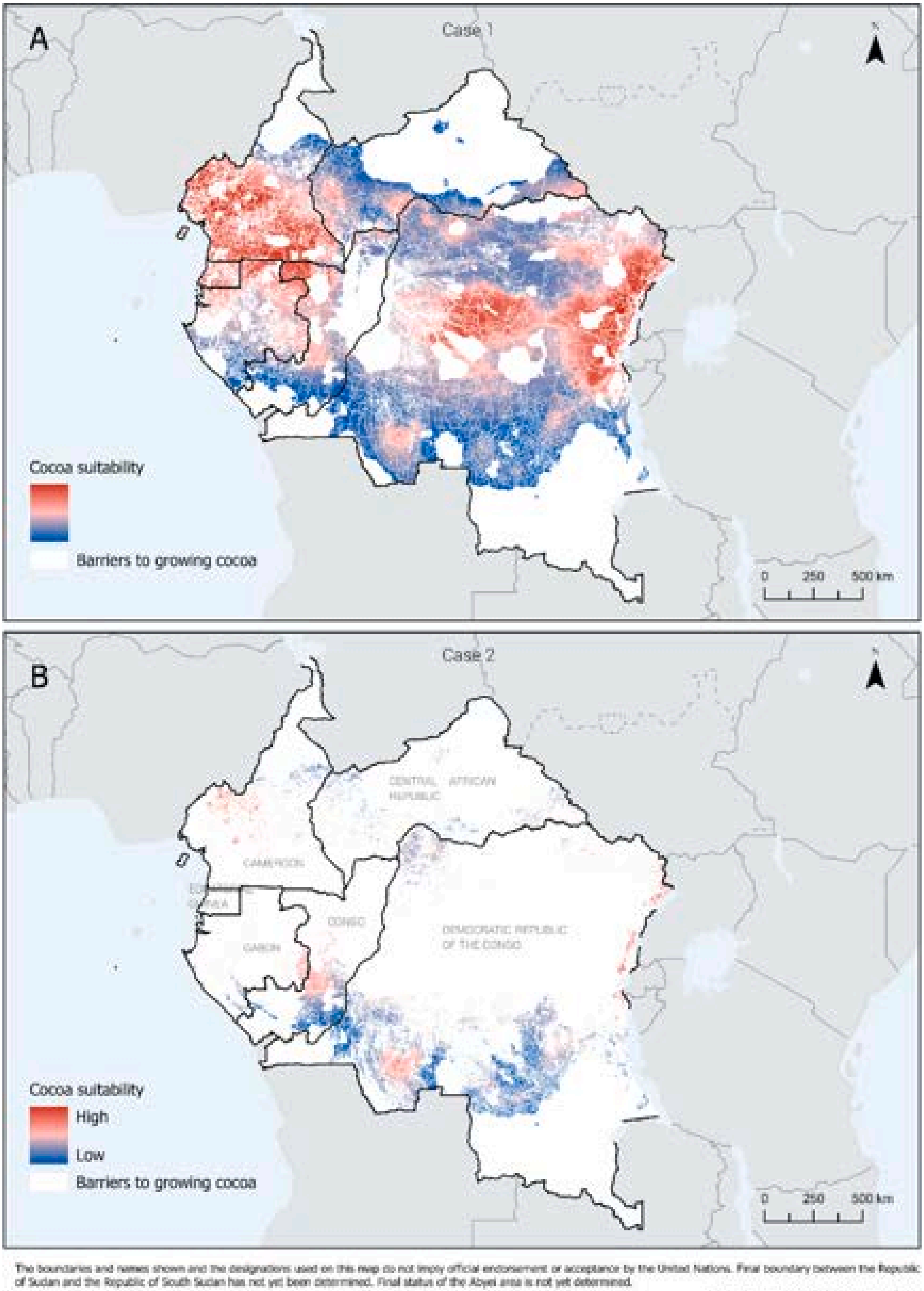

Fig. 2. A. Area available and suitability for cocoa (case 1). B. Area available and suitability for cocoa with forest areas removed (case 2). White areas represent biophysical or legal barriers to cocoa growing while the colour gradient represents climatic suitability.

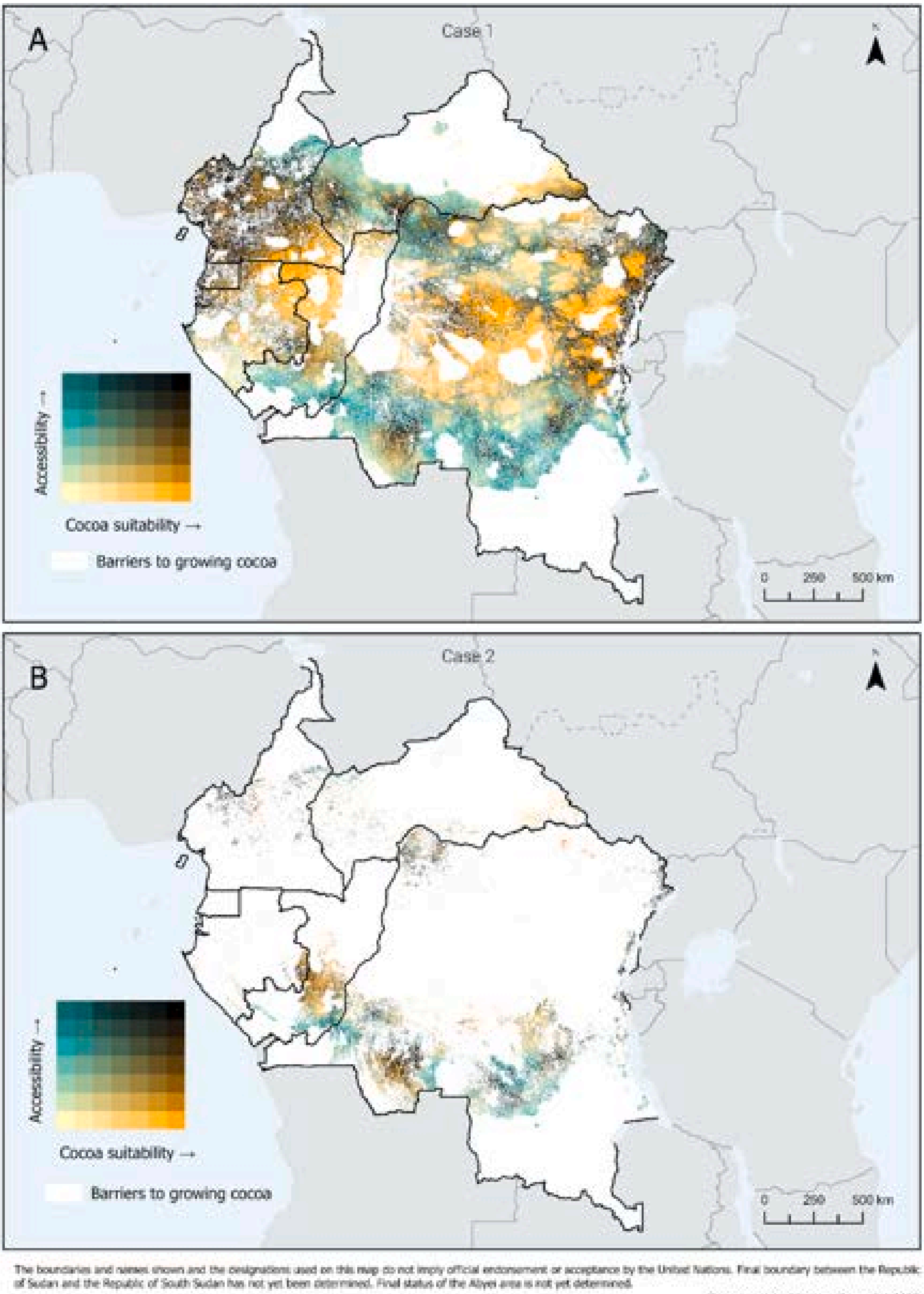

Fig. 3. A. Accessibility and cocoa suitability (case 1). B. Accessibility and cocoa suitability with forest areas removed (case 2). Accessibility is represented by travel time to the nearest major city. Black areas are both highly accessible and suitable for growing cocoa.

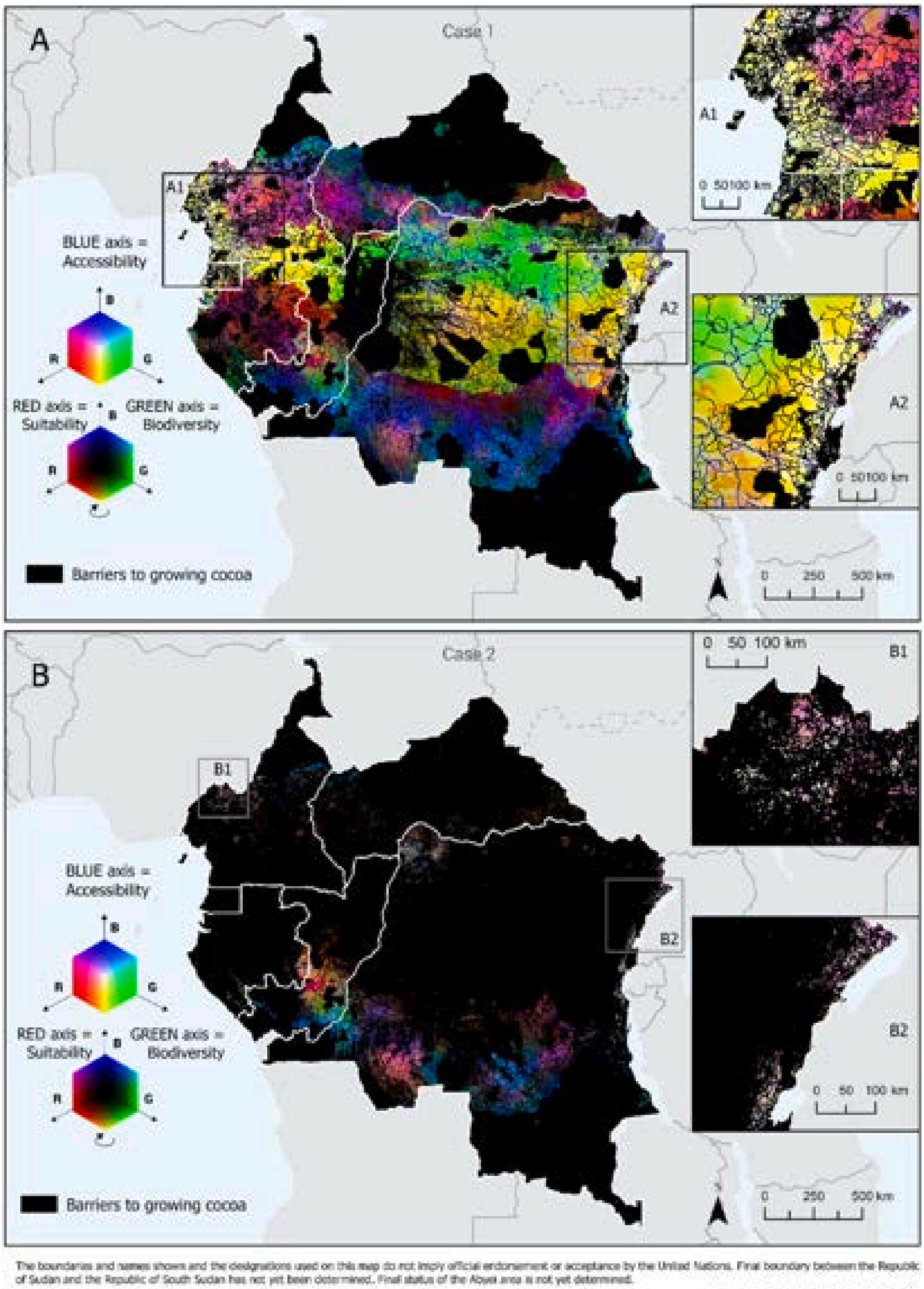

Fig. 4. RGB plots showing accessibility, biodiversity significance and cocoa suitability (case 1). Case 2 shows the same with forest areas removed. The colours on the plots are presented in a 3-dimensional cube representing metrics in each axis: cocoa suitability (red), biodiversity significance (green), and accessibility (blue). The 3-D cube is shown in two views, to allow visualization of a broader range of colours. In the front view (top cube), each face shows the highest value of one metric and variable values of the other two. Lighter combinations of colours indicate higher combined values of the three metrics. White indicates areas with the highest values of all three metrics. In the back view (bottom cube), each face shows the lowest value of one metric and variable values of the other two. Black indicates areas with the lowest values of all three metrics. Note that black also represents barriers to growing cocoa (refer to Figs. 2 or 3 for the delineation of the biophysical and legal barriers to growing cocoa). Pure colours (red, green, blue) indicate a high value in one metric and low values in the others, while mixed colours (i.e., yellow, magenta, cyan) indicate high values in two metrics. Yellow (combination of red and green) indicates areas with high biodiversity significance and cocoa suitability. Similarly, cyan (combination of green and blue) indicates high biodiversity significance and accessibility, and magenta (combination of red and blue) shows areas with high cocoa suitability and accessibility.

biodiversity values due to existing forest degradation. Such areas might, therefore, be considered to have opportunities for sustainable agricultural development. According to Cordero-Sancho and Bergen (2018), in the forest areas of Cameroon and the Republic of Congo, 76 percent of the clearings were located within 1 km distance from either a road or a river. Such considerations should be included in local planning. Including spatial data on forest condition in combination with accessibility could help in identifying areas combining potentially lower risk and higher opportunity for biodiversity and people.

Policies to halt imported deforestation pose a risk to national economies in forested countries where agricultural export commodities are a major part of economic development trajectories (e.g., (Eba'a Atyi et al., 2022)). They also pose a risk to local livelihoods, particularly where smallholder farmers mainly produce commodities like cocoa. These socio-economic impacts need further understanding. Challenges include the lack of consensus on forest and deforestation definitions and monitoring methods (Eba'a Atyi et al., 2022). Cameroon, for example, distinguishes the permanent and the non-permanent forest domain. The latter in principle being available for economic development like commodity agriculture. Development of such areas would be considered deforestation as per the new EU law on imported deforestation. Yet, without alternative income sources from maintaining such areas as forests (e.g., payments for carbon sequestration), such countries may have few alternatives to achieve their development objectives. Moreover, some types of land use change may be less detrimental to (local) biodiversity than others, and well managed perennial commodity production systems could outweigh some more destructive economic activity options such as open cast mining or industrial plantations that transform whole landscapes into monocultures (Maney et al., 2022; Niether et al., 2020).

Even if the Congo Basin countries implemented a zero-deforestation policy across all forested areas, western Cameroon and northeastern and eastern edges of DRC could still be at risk of biodiversity loss due to the conversion of other land use types (like herbaceous vegetation in the savanna-forest transition zone) to cocoa. Similarly, existing agricultural systems in these areas could be at risk of losing tree cover under pressures to increase food and commodity production. These include, for example, areas surrounding Beni and running adjacent to Virunga National Park. While large-scale cocoa expansion in eastern DRC is unlikely as long as armed conflict and the risk of Ebola outbreaks persist, the potential for such expansion in these areas in the future cannot be dismissed. Unplanned cocoa expansion has a high risk of increasing the rate of deforestation and biodiversity loss in the primary forests and other ecosystems of the Congo Basin. This would be detrimental to the flora and fauna of the region while simultaneously worsening the impacts of climate change, reducing soil fertility, and spreading diseases.

This study is not intended to guide implementation of areas where cocoa cultivation should take place, e.g., in areas of high suitability, high accessibility and low biodiversity significance, as the resolution of the data does not allow us to make such decisions on a local scale. Yet, it allows the broad prioritisation of such areas for further targeted assessment using similar criteria at the local level. Finer scale assessments and field studies should be conducted to inform any on-ground planning and development of commodity cropping. Furthermore, localised planning should include social impact assessments to understand the implications of cocoa expansion and identify the potential problems and benefits for local communities. These assessments should focus on the needs, dependencies and vulnerabilities of women in the areas where cocoa expansion is being considered, since in some contexts women are known to face inequalities and disadvantages in cocoa farming compared to men (Danso-Abbeam et al., 2020; Friedman et al., 2019).

Finally, yields are generally only about half the potential in the region, with much variation (Lescuyer et al., 2020). Supporting farmers to achieve higher yields in both simple and complex cocoa cropping systems would be beneficial (Wessel and Quist-Wessel, 2015). The choice of production systems should be informed by local level objectives, with for example simpler, more intensive systems near urban areas or where market access is good but away from important biodiversity areas (protected or not). Conversely, more diverse systems (e.g., agroforestry) can be promoted near areas of high biodiversity and carbon values or where market access is limited and farmers are better off with a more diversified system.

4.2. Spatial approach to identify crop expansion and biodiversity risk

Below, we highlight some caveats and limitations with our approach. There is limited occurrence data on cocoa plantations in the Congo Basin and, since cocoa is mostly grown under tree canopy cover in the region, it is challenging to accurately detect plantations using remote sensing methods. This lack of continuous long-term data on the spatial extent of cocoa cultivation makes it difficult to estimate potential areas of expansion as this is likely to occur from areas where cocoa is already grown.

To explore remaining areas suitable and available for cocoa outside forests, we excluded forest classes with canopy cover greater than 15 % (Copernicus 2019 landcover data (Buchhorn et al., 2020)), whereas EU legislation on imported deforestation uses a 10 % threshold. This means some of our remaining areas would be considered forest under the latter definition. Therefore, we acknowledge that the forest dataset we used does not align fully with the "forest" definition by the new EU legislation. Removing forests > 15 % forest cover also removes known cocoa production areas in the region (e.g., in central, southeastern and southwestern Cameroon), illustrating the difficulty of distinguishing cocoa agroforestry systems from forest. This raises potential issues for monitoring the role of cocoa production in deforestation depending on the forest definition and whether this definition can be accurately mapped.

The assumed biophysical barriers to cocoa cultivation include wetlands, peatlands and slope above 20 %. In reality, these aspects may affect suitability for cocoa on a continuous scale (e.g., for slope) as is the case for climatic suitability. However, data on the relationship between cocoa productivity and these aspects is limited. For slope, there are some data available for Papua New Guinea (Singh et al., 2021), but not for any of the Congo Basin countries.

Our climate suitability model used a species distribution modelling approach to assess the similarity of climate in the study area with climate at global cocoa locations. This was necessary because little is known about the cocoa-climate relationship in the Congo Basin itself. Model parameters were carefully selected to avoid overfitting, although uncertainty remains about whether the full range of potential climate conditions was adequately reflected. Furthermore, interpolated climate data were used for the climate model. It is known that such climate data may have errors, especially in regions with low density of historic climate observations (Fick and Hijmans, 2017).

While we endeavoured to use the best available spatial datasets, our approach faces data-related challenges including inadequate ground data (e.g., locations of cocoa plantations), varying spatial scales and resolutions of data layers, and data availability across different time periods. As expected for analysis at this spatial scale, the biodiversity data are representative of species groups with available information and the underlying AOH maps contain unknown omission and commission errors.

Finally, in this exploratory study, we focused on a limited set of assumed physical and legal barriers that could prevent cocoa from growing in certain areas. Future studies could consider more layers such as soil types, land tenure and socio-economic contexts in the region. While such datasets may not exist in sufficiently high quality for the entire Congo Basin, they may be available for smaller areas.

5. Conclusions

Our analysis identified areas, mostly in the central belt of the Congo Basin, where cocoa expansion could accelerate biodiversity loss. We find that some highly biodiverse areas that are both highly suitable for cocoa and highly accessible are found near important protected areas. This poses a potential risk but also presents a local economic opportunity for sustainable land use. There are non-forested areas that are suitable for cocoa that could be considered for development under a no-deforestation policy, though this may still impact important (non-forest) biodiversity values. Much existing shaded cocoa is detected as forest in current land cover datasets. In such areas, the maintenance of shaded systems should be promoted and can contribute to maintaining at least some of the values and functions of forest, including carbon sequestration and significant biodiversity values.

We present a spatial approach to identify possible areas of future cocoa expansion or intensification and the consequent biodiversity risk areas, including those that are outside of forests, using global openly accessible data sources. The approach in this study can be replicated for other commodities and regions with inadequate national level data. Further studies can incorporate additional data layers as needed and relevant, to consider different constraints and opportunities. The findings can help policymakers and practitioners in the agricultural sector identify areas potentially most at risk of biodiversity loss from cocoa expansion at the national level and balance trade-offs with other values, such as carbon sequestration, other ecosystem services, and local and national economic development objectives.

CRediT authorship contribution statement

Vignesh Kamath: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Marieke Sassen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Andy Arnell:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis. **Arnout van Soesbergen:** Writing – review & editing, Validation, Methodology, Conceptualization. **Christian Bunn:** Writing – review & editing, Software, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The input data used in the analyses are from published sources that have been cited in the methods section. Intermediate data generated in this study will be made available upon reasonable request.

Dataset supporting 'Identifying areas where biodiversity is at risk from potential cocoa expansion in the Congo Basin' (Original data) (Zenodo)

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.109216.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage, *300*. Fao, *Rome*, p. D05109.

Bele, M.Y., Sonwa, D.J., Tiani, A.-M., 2015. Adapting the Congo Basin forests management to climate change: Linkages among biodiversity, forest loss, and human well-being. For. Policy Econ. *50*, 1–10.

Boria, R.A., Olson, L.E., Goodman, S.M., Anderson, R.P., 2014. Spatial filtering to reduce sampling bias can improve the performance of ecological niche models. Ecol. Model. *275*, 73–77. https://doi.org/10.1016/j.ecolmodel.2013.12.012.

Breiman, L., 2001. Random forests. Mach. Learn. *45* (1), 5–32. https://doi.org/10.1023/A:1010933404324.

Brooks, T.M., Pimm, S.L., Akçakaya, H.R., Buchanan, G.M., Butchart, S.H.M., Foden, W., Hilton-Taylor, C., Hoffmann, M., Jenkins, C.N., Joppa, L., Li, B.V., Menon, V., Ocampo-Peñuela, N., Rondinini, C., 2019. Measuring Terrestrial Area of Habitat (AOH) and Its Utility for the IUCN Red List. Trends Ecol. Evol. *34* (11), 977–986. https://doi.org/10.1016/j.tree.2019.06.009.

Buchhorn, M., Smets, B., Bertels, L., Roo, B. De, Lesiv, M., Tsendbazar, N.-E., Herold, M., & Fritz, S. (2020). *Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2019: Globe*. https://doi.org/10.5281/ZENODO.3939050.

Carodenuto, S., 2019. Governance of zero deforestation cocoa in West Africa: New forms of public–private interaction. Environ. Policy Gov. *29* (1), 55–66.

CBI. (2023). *In Ituri Province in DRC, a Sustainable Cocoa Coalition is Shaping up to Protect Okapi Wildlife Reserve*. News Story Published by the Congo Basin Institute. 〈https://www.cbi.ucla.edu/in-ituri-province-in-drc-a-sustainable-cocoa-coalition-is-shaping-up-to-protect-okapi-wildlife-reserve-english-and-french〉. Accessed 28 June 2023.

Clough, Y., Faust, H., Tscharntke, T., 2009. Cacao boom and bust: sustainability of agroforests and opportunities for biodiversity conservation. Conserv. Lett. *2* (5), 197–205.

Cordero-Sancho, S., Bergen, K.M., 2018. Relationships of agricultural land use to an expanded road network within tropical forest landscapes of Cameroon and Republic of the Congo. Prof. Geogr. *70* (1), 60–72. https://doi.org/10.1080/00330124.2017.1325752.

R. Core Team. (2021). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. 〈https://www.r-project.org/〉.

Dalimier, J., Achard, F., Delhez, B., Desclée, B., Bourgoin, C., Eva, H., …, & & Defourny, P. (2022). Distribution of forest types and changes in their classification. In R. Eba'a Atyi, F. Hiol Hiol, G. Lescuyer, P. Mayaux, P. Defourny, N. Bayol, F. Saracco, D. Pokem, R. Sufo Kankeu, & R. Nasi (Eds.), The Forests of the Congo Basin: State of the Forests 2021 (pp. 3–34). CIFOR. https://doi.org/10.17528/cifor/008700.

Danielson, J.J., & Gesch, D.B. (2011). Global multi-resolution terrain elevation data 2010 (GMTED2010). Open-File Re*port*. https://doi.org/10.3133/OFR20111073.

Danso-Abbeam, G., Baiyegunhi, L.J.S., Ojo, T.O., 2020. Gender differentials in technical efficiency of Ghanaian cocoa farms. Heliyon *6*, 5.

Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T.A., Page, S.E., Bocko, Y.E., Ifo, S.A., 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. *7639*, *542* Nature 2017 *542* (7639), 86–90. https://doi.org/10.1038/nature21048.

De Beenhouwer, M., Aerts, R., Honnay, O., 2013. A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. Agric., Ecosyst. Environ. *175*, 1–7.

De Beule, H., Jassogne, L.T.P., & van Asten, P.J.A. (2014). Cocoa: Driver of deforestation in the Democratic Republic of the Congo? CCAFS Working Paper. 〈http://www.ccafs.cgiar.org〉.

Descals, A., Wich, S., Meijaard, E., Gaveau, D.L.A., Peedell, S., Szantoi, Z., 2021. High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. Earth Syst. Sci. Data *13* (3), 1211–1231. https://doi.org/10.5194/essd-13-1211-2021.

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., McClean, C., Osborne, P.E., Reineking, B., Schröder, B., Skidmore, A.K., Zurell, D., Lautenbach, S., 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography *36* (1), 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x.

Dorosh, P., Wang, H.G., You, L., Schmidt, E., 2012. Road connectivity, population, and crop production in Sub-Saharan Africa. Agric. Econ. *43* (1), 89–103. https://doi.org/10.1111/J.1574-0862.2011.00567.X.

Eba'a Atyi, R., Ingram, V., Lescuyer, G., Lang, C.C., Tchoumba, B., Defo, L., Gourlet-Fleury, S., Guizol, P., Sonwa, D.J., Mbonayem, L., Berger, V., & Harmand, J.-M. (2022). Addressing imported deforestation and zero deforestation commitments. In R. Eba'a Atyi, F. Hiol Hiol, G. Lescuyer, P. Mayaux, P. Defourny, N. Bayol, F. Saracco, D. Pokem, R. Sufo Kankeu, & R. Nasi (Eds.), The Forests of the Congo Basin: State of the Forests 2021 (pp. 213–238). CIFOR. https://doi.org/10.17528/cifor/008700.

Ernst, C., Mayaux, P., Verhegghen, A., Bodart, C., Christophe, M., Defourny, P., 2013. National forest cover change in Congo Basin: deforestation, reforestation, degradation and regeneration for the years 1990, 2000 and 2005. In: Global Change Biology, *19*, pp. 1173–1187.

European Union. (2023). Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023. *Official Journal of the European Union 9.6.2023 - L 150/206*. ⟨https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1115⟩.

FAO. (2020). *FAOSTAT. Food and agriculture data.* Statistics Division, Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/faostat/en. Accessed March 2022.

Feintrenie, L., 2014. Agro-industrial plantations in Central Africa, risks and opportunities. Biodivers. Conserv. *23* (6), 1577–1589.

Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int. J. Climatol. *37* (12), 4302–4315. https://doi.org/10.1002/JOC.5086.

Friedman, R., Hirons, M.A., Boyd, E., 2019. Vulnerability of Ghanaian women cocoa farmers to climate change: a typology. Clim. Dev. *11* (5), 446–458.

Global Biodiversity Information Facility (GBIF). (2015). *Global Biodiversity Information Facility: free and open access to biodiversity data.* ⟨http://www.gbif.org/⟩ Accessed 13 Oct 2015.

Gockowski, J., Sonwa, D., 2011. Cocoa intensification scenarios and their predicted impact on CO 2 emissions, biodiversity conservation, and rural livelihoods in the Guinea rain forest of West Africa. Environ. Manag. *48*, 307–321.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. *202*, 18–27. https://doi.org/10.1016/J.RSE.2017.06.031.

Government of Cameroon. (2021). *Roadmap to Deforestation-Free Cocoa in Cameroon. Towards a sustainable cocoa sector that protects forests and enhances farmers' livelihoods in Cameroon. Joint Framework For Action*. ⟨https://www.idhsustainabletrade.com/uploaded/2021/01/RDFC-Framework-4.5-RGB-Small.pdf⟩. Accessed 18 February 2021.

Hand, D.J., Till, R.J., 2001. A Simple Generalisation of the Area Under the ROC Curve for Multiple Class Classification Problems. Mach. Learn. *45* (2), 171–186 https://doi.org/https://doi.org/10.1023/A:1010920819831.

Hanson, L.W., Bourke, R.M., & Yinil, D.S. (1998). *Cocoa and coconut growing environments in Papua New Guinea: A guide for research and extension activities*.

Harris, N., Goldman, E.D., & Gibbes, S. (2019). *Spatial database of planted trees (SDPT Version 1.0)*. Accessed through Global Forest Watch on 21 January 2022. ⟨www.globalforestwatch.org⟩.

ICCO. (2017). Quarterly Bulletin of Cocoa Statistics. *Vol. XLIII, No. 1, Cocoa Year 2016/17*.

Instituto Nacional De Estadistica E Informatica. (2013). *IV Censo Nacional Agropecuar*io 2012: *Resultados definitivos*.

IUCN. (2019). *The IUCN Red List of Threatened Species. Version 2019 -2*. ⟨http://www.iucnredlist.org⟩.

Jagoret, P., Michel-Dounias, I., Snoeck, D., Ngnogué, H.T., Malézieux, E., 2012. Afforestation of savannah with cocoa agroforestry systems: a small-farmer innovation in central Cameroon. Agrofor. Syst. *86*, 493–504.

Jung, M., Dahal, P.R., Butchart, S.H.M., Donald, P.F., De Lamo, X., Lesiv, M., Kapos, V., Rondinini, C., Visconti, P., 2020. A global map of terrestrial habitat types. *7:1*, *7* Sci. Data *2020* (1), 1–8. https://doi.org/10.1038/s41597-020-00599-8.

Läderach, P., Martinez-Valle, A., Schroth, G., Castro, N., 2013. Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. Clim. Change *119* (3–4), 841–854.

Laurance, W.F., Sayer, J., Cassman, K.G., 2014. Agricultural expansion and its impacts on tropical nature. Trends Ecol. Evol. *29* (2), 107–116. https://doi.org/10.1016/j.tree.2013.12.001.

Lescuyer, G., Bassanaga, S., 2021. Positive influence of certification on the financial performance of cocoa production models in Cameroon. Front. Sustain. Food Syst. *5*, 743079.

Lescuyer, G., Boutinot, L., Goglio, P., Bassanaga, S., 2020. Analyse de la chaîne de valeur du cacao au Cameroun. Rapport pour l'Union Européenne, DG DEVCO. Value Chain Anal. Dev. Proj. (VCA4D CTR) *75–804. 2016/3*.

Li, F., Mo, D., 2016. The burgeoning chocolate market in China. Econ. Choc. *383*.

Liaw, A., Wiener, M., 2002. Classif. Regres. Random *2* (3). ⟨http://www.stat.berkeley.edu/⟩.

Maney, C., Sassen, M., Hill, S.L.L., 2022. Modelling biodiversity responses to land use in areas of cocoa cultivation. Agric., Ecosyst. Environ. *324*, 107712.

Maus, V., Giljum, S., Gutschlhofer, J., da Silva, D.M., Probst, M., Gass, S.L.B., Luckeneder, S., Lieber, M., McCallum, I., 2020. A global-scale data set of mining areas. *7:1*, *7* Sci. Data *2020* (1), 1–13. https://doi.org/10.1038/s41597-020-00624-w.

Mayaux, P., Malingreau, J.-P., 2000. Le couvert forestier d'Afrique centrale: Un nouvel état des lieux. Bull. Des. Séances= Meded. Der Zitt. *46* (4), 475–486.

Megevand, C., 2013. Deforestation Trends in the Congo Basin: Reconciling Economic Growth and Forest Protection.

Mielke, M.S., Almeida, A.-A.F. de, Gomes, F.P., 2005. Photosynthetic traits of five neotropical rainforest tree species: interactions between light response curves and leaf-to-air vapour pressure deficit. Braz. Arch. Biol. Technol. *48* (5), 815–824. https://doi.org/10.1590/S1516-89132005000600018.

MINEPAT (2020). *National Development Strategy–Cameroon 2030. Ministère de la Planification et de l'Aménagement du Territoire.*

Molinario, G., Hansen, M., Potapov, P., Tyukavina, A., Stehman, S., 2020. Contextualizing landscape-scale forest cover loss in the Democratic Republic of Congo (DRC) between 2000 and 2015. Land *9* (1), 23.

Niether, W., Jacobi, J., Blaser, W.J., Andres, C., Armengot, L., 2020. Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. Environ. Res. Lett. *15* (10), 104085 https://doi.org/10.1088/1748-9326/ABB053.

Nijmeijer, A., Lauri, P.-É., Harmand, J.-M., Saj, S., 2019. Carbon dynamics in cocoa agroforestry systems in Central Cameroon: afforestation of savannah as a sequestration opportunity. Agrofor. Syst. *93*, 851–868.

Norris, K., Asase, A., Collen, B., Gockowksi, J., Mason, J., Phalan, B., Wade, A., 2010. Biodiversity in a forest-agriculture mosaic–The changing face of West African rainforests. Biol. Conserv. *143* (10), 2341–2350.

Ordway, E.M., Asner, G.P., Lambin, E.F., 2017. Deforestation risk due to commodity crop expansion in sub-Saharan Africa. Environ. Res. Lett. *12* (4), 044015 https://doi.org/10.1088/1748-9326/AA6509.

Robin, X., Turck, N., Hainard, A., Tiberti, N., Lisacek, F., Sanchez, J.-C., Müller, M., 2011. pROC: an open-source package for R and S+ to analyze and compare ROC curves. BMC Bioinforma. *12* (1), 77. https://doi.org/10.1186/1471-2105-12-77.

Ruf, F., Schroth, G., 2004. Chocolate forests and monocultures: a historical review of cocoa growing and its conflicting role in tropical deforestation and forest conservation. *Agroforestry and Biodiversity Conservation in Tropical Landscapes*. Washington. Island Press, pp. 107–134.

Ruf, F., Schroth, G., Doffangui, K., 2015. Climate change, cocoa migrations and deforestation in West Africa: What does the past tell us about the future? *Sustainability*. Science *10*, 101–111.

Saj, S., Jagoret, P., Etoa, L.E., Eteckji Fonkeng, E., Tarla, J.N., Essobo Nieboukaho, J.-D., Mvondo Sakouma, K., 2017. Lessons learned from the long-term analysis of cacao yield and stand structure in central Cameroonian agroforestry systems. Agric. Syst. *156*, 95–104. https://doi.org/10.1016/j.agsy.2017.06.002.

Sassen, M., van Soesbergen, A., Arnell, A.P., Scott, E., 2022. Patterns of (future) environmental risks from cocoa expansion and intensification in West Africa call for context specific responses. Land Use Policy *119*, 106142. https://doi.org/10.1016/J.LANDUSEPOL.2022.106142.

Schroth, G., Läderach, P., Martinez-Valle, A.I., Bunn, C., Jassogne, L., 2016. Vulnerability to climate change of cocoa in West Africa: Patterns, opportunities and limits to adaptation. Sci. Total Environ. *556*, 231–241. https://doi.org/10.1016/j.scitotenv.2016.03.024.

Shi, T., Horvath, S., 2006. Unsupervised Learning With Random Forest Predictors. J. Comput. Graph. Stat. *15* (1), 118–138. https://doi.org/10.1198/106186006X94072.

Singh, K., Fuentes, I., Fidelis, C., Yinil, D., Sanderson, T., Snoeck, D., Minasny, B., Field, D.J., 2021. Cocoa suitability mapping using multi-criteria decision making: An agile step towards soil security. Soil Secur. *5*, 100019 https://doi.org/10.1016/J.SOISEC.2021.100019.

Sonwa, D.J., Nkongmeneck, B.A., Weise, S.F., Tchatat, M., Adesina, A.A., Janssens, M.J.J., 2007. Diversity of plants in cocoa agroforests in the humid forest zone of Southern Cameroon. Biodivers. Conserv. *16*, 2385–2400.

Tegegne, Y.T., Lindner, M., Fobissie, K., Kanninen, M., 2016. Evolution of drivers of deforestation and forest degradation in the Congo Basin forests: Exploring possible policy options to address forest loss. Land Use Policy *51*, 312–324.

Theobald, D.M., Kennedy, C., Chen, B., Oakleaf, J., Baruch-Mordo, S., Kiesecker, J., 2020. Earth transformed: detailed mapping of global human modification from 1990 to 2017. *Earth System Science*. Data *12* (3), 1953–1972.

Tondoh, J.E., Kouamé, F.N., Guéi, A.M., Sey, B., Koné, A.W., Gnessougou, N., 2015. Ecological changes induced by full-sun cocoa farming in Côte d'Ivoire. Glob. Ecol. Conserv. *3*, 575–595.

Tyukavina, A., Hansen, M.C., Potapov, P., Parker, D., Okpa, C., Stehman, S.V., Kommareddy, I., Turubanova, S., 2018. Congo Basin forest loss dominated by increasing smallholder clearing. Sci. Adv. *4* (11) https://doi.org/10.1126/sciadv.aat2993.

UK Public General Acts. (2021). *Use of forest risk commodities in commercial activity.* Section 116 and Schedule 17 of the Environment Act 2021. UK Government. ⟨https://www.legislation.gov.uk/ukpga/2021/30/section/116/enacted⟩.

UNEP-WCMC & IUCN (2021). *Protected Planet: The World Database on Protected Areas (WDPA)*, November 2021, Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.

United States Congress. (2021). *S.2950 - 117th Congress (2021-2022): FOREST Act of 2021. (2021, October 6)*. ⟨https://www.congress.gov/bill/117th-congress/senate-bill/2950⟩. Accessed 29 June 2023.

Vancutsem, C., Achard, F., Pekel, J.-F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J., Aragão, L.E.O.C., Nasi, R., 2021. Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. Sci. Adv. *7* (10) https://doi.org/10.1126/sciadv.abe1603.

Varela, S., Anderson, R.P., García-Valdés, R., Fernández-González, F., 2014. Environmental filters reduce the effects of sampling bias and improve predictions of ecological niche models. Ecography *37* (11), 1084–1091. https://doi.org/10.1111/j.1600-0587.2013.00441.x.

Weiss, D.J., Nelson, A., Gibson, H.S., Temperley, W., Peedell, S., Lieber, A., Hancher, M., Poyart, E., Belchior, S., Fullman, N., 2018. A global map of travel time to cities to assess inequalities in accessibility in 2015. Nature *553* (7688), 333–336.

Wessel, M., Quist-Wessel, P.M.F., 2015. Cocoa production in West Africa, a review and analysis of recent developments. NJAS - Wagening. J. Life Sci. *74–75*, 1–7. https://doi.org/10.1016/J.NJAS.2015.09.001.

Wilkie, D., Shaw, E., Rotberg, F., Morelli, G., Auzel, P., 2000. Roads, Development, and Conservation in the Congo Basin. Conserv. Biol. *14* (6), 1614–1622. https://doi.org/10.1111/j.1523-1739.2000.99102.x.

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J.C., Sampson, C.C., Kanae, S., Bates, P.D., 2017. A high-accuracy map of global terrain elevations. Geophys. Res. Lett. *44* (11), 5844–5853.