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Effects of the Congo Basin Rainforest on Rainfall Patterns

Report commissioned by the Norwegian Environment Agency

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Report title	Effects of the Congo Basin Rainforest on Rainfall Patterns
Project No	107388
Institution	NORCE Climate and Environment
Client(s)	Norwegian Environment Agency
Classification:	Public
Report No.	12-2023, Climate and Environment
No. of pages	30
Date of publ.:	October 2023
ISBN	978-82-8408-306-3
CC-license	CC BY 4.0
Citation	Barimalala, R., Kolstad, E. W., Parker, D. J., & Williams, D. A. (2023). Effects of the Congo Basin Rainforest on Rainfall Patterns. Report no. 12-2023, NORCE Climate and Environment.
Photo Credit	Massif du Mayombe, taken on 10 January 2014 in Congo around Dolisie Doumanga. Photo by jbdodane / Flickr.
Geographical area	Africa
Keywords	Africa, Congo, Rainforest, Deforestation, Climate, Rainfall

Summary

Large-scale deforestation in the Congo Basin has an impact on rainfall patterns, both in the Basin and beyond. Factors like socio-economic drivers contribute to ongoing deforestation, and forest loss rates are expected to increase. The mechanisms linking deforestation and rainfall are complex. On a local scale, deforested areas might experience increased rainfall, but adjacent forests could see reduced rainfall. On larger scales, widespread deforestation can reduce overall rainfall in large areas. These changes can impact agriculture, with delayed rainfall and shorter rainy seasons affecting crop yields. By 2100, projected forest loss in the Congo Basin may reduce annual rainfall by 8-10%. However, uncertainties remain due to limited data and understanding of rainfall drivers and interactions in the region.

Revisions

Version	Date	Approved by	Comment
1	25.09.2023	Erik Kolstad	Submitted to the Norwegian Environment Agency
2	24.10.2023	Erik Kolstad	Minor changes (typos) before online publication

Summary

Large-scale deforestation likely leads to a decrease in rainfall over a deforested area. It also has the potential to alter wind systems and moisture transport patterns so that neighbouring areas are also affected. While the impacts of the Amazon deforestation on the local, regional, and global climate have been studied extensively, deforestation in the Congo Basin and its consequences on rainfall over the African continent have received less attention. In this report we summarize the currently available knowledge on the effects of the Congo Basin rainforest on rainfall.

Socio-economic studies and data show various underlying and proximate drivers contributing to ongoing deforestation in the Congo Basin, with all countries experiencing net forest loss between 2000 and 2020. Since 2015, forest loss appears to have been relatively stable in the Democratic Republic of Congo, Republic of Congo, Equatorial Guinea, and Gabon, while appearing to increase in the Central African Republic and Cameroon. Several studies project that rates of forest loss in the Congo Basin will increase in the coming years and decades.

Deforestation observed in the Congo Basin is not evenly distributed in spatial terms. Apart from varying levels of forest loss across Congo Basin countries, different intensities of deforestation are observed across locales within each country. Areas with higher observed forest loss include those along road networks, areas subject to food crop production and industrial plantations, mining areas, and areas close to refugee camps or that have experienced civil unrest.

The physical mechanisms that dictate the rainfall response to deforestation are complex. Trees carry moisture from the soil to the air through their leaves, and most of the sun's energy arriving at the surface is used up in this process of *evapotranspiration*, which is a combined term encapsulating loss of soil water both by *evaporation* and by *transpiration* from leaves. There is usually higher evapotranspiration over forests than over deforested land. In dry periods, evapotranspiration is more strongly maintained over forested regions than it is over deforested areas, when the upper levels of soil become dry and shallow-rooted plants can no longer transpire. There are indications that the rainy season over the Congo and neighbouring regions becomes shorter following deforestation.

A secondary effect is that deforested areas have a brighter surface than the remaining forest, which means that the deforested area absorbs less of the sun's energy. This cools the deforested surface, but the effect is smaller than that of reduced evapotranspiration, and the net effect is still typically warming and drying over the deforested region.

As there are feedback mechanisms linking temperature, humidity, and wind patterns, the net response of deforestation on rainfall depends on the spatial scale considered. On the local scale (10–100 km) there is evidence of increased rainfall over the deforested area and reduced rainfall over adjacent forest. Although air over the deforested area is drier, moisture is supplied by winds from adjacent forest, and the hot air over deforested land rises and triggers clouds. Locally, this increase in rainfall probably mitigates the drying that is caused directly by deforestation, but the reduction of rain on the remaining forest is a concern. On larger spatial scales, widespread deforestation reduces the average evapotranspiration over the area, and this is seen in climate models to be associated with a reduction in average rainfall over the continent.

On continental scales, rainfall is also influenced through feedback mechanisms with wind patterns. Rainfall over a region generally comes from three main moisture sources: moisture transported by the atmosphere from remote areas, local evapotranspiration and water vapour that is already in the atmosphere. The Congo Basin is a net moisture sink; 33% more atmospheric water vapour is imported into the region from neighbouring areas than what is exported. Most of the imported moisture derives from East Africa.

Much of the moisture from evapotranspiration in the Congo rainforest is recycled and contributes 25%–85% of the annual rainfall within the Congo Basin. Moisture from the Basin also provides about 40% of the Sahelian Sudan annual rainfall and almost half of the Ethiopian highland rainfall during June–August.

Modelling studies of the impacts of deforestation on rainfall suggest that a complete replacement of the Congo rainforest with grassland leads to a decrease of 16% (+/– 17%) in annual rainfall in the Basin. Outside the Basin, South Sudan, Sahelian Sudan, Burkina-Faso, southern Niger, Mali and northern Nigeria may experience up to 40% of decrease in rainfall, while the southern equatorial areas show an increase in rainfall. There are indications that rainfall deficit due to a 10 percentage-point loss in forest cover causes a reduction in crop yields by 1.25%.

A complete removal of the Congo rainforest would lead to a delay in rainfall onset, a shorter rainy season and a change in the spatial distribution of the rainfall both within the Congo Basin and the surrounding countries. These rainfall characteristics are critical to the agricultural sector and any change could impact crop yields. In Ethiopia, a 5-day delay in rainfall onset could lead to a loss of 1.5% in crop production, while a 5-day shorter rainy season decreases the production by 1.1%.

Between 2015 and 2100, the projected forest loss in the Congo Basin is estimated to reduce the Basin's annual rainfall by 16.5 mm (+/– 6.2 mm), equivalent to a rainfall decline of 8%–10%. The Western Congo, where forest loss is projected to be highest, will experience the strongest rain depletion.

There are large uncertainties in the contribution of the Congo rainforest's evapotranspiration on total rainfall and on the potential impacts of deforestation on rainfall. These stem from the lack of observations in the Basin and from a lack of understanding of the various rainfall drivers and their interactions with each other.

Table of contents

1. Introduction

The overall impacts of deforestation on rainfall have been a subject of many studies for the past few decades. In the sixth assessment report of the IPCC, it is concluded that large-scale deforestation has likely decreased evapotranspiration and rainfall and increased runoff over deforested regions (IPCC, 2021). Results from nine global climate models confirm that on a scale of 20 million km^2, deforestation leads to a decrease in rainfall of up to –37 (+/– 54) mm/year over a deforested area (Boysen et al., 2020).

In the tropical rainforest basins (Amazon, Congo and Southeast Asia), the extension of agricultural activities has led to a rapid loss of forests across the tropics, thus changes in rainfall and runoff. The impacts of the Amazon deforestation on local, regional, and global climate have attracted a lot of attention due to the size of the Amazon and have been studied extensively. In contrast, interest in the increasing deforestation in the Congo Basin and its consequences on rainfall over the African continent only started recently.

The socio-economic development of the Congo Basin area and the surrounding countries are heavily dependent on rain-fed agriculture. Any changes in the patterns, distribution, and characteristics of rainfall in the region due to deforestation or other causes will, therefore, have significant impacts not only in the agricultural sector but also the livelihood of the population.

In this report, we assess the possible consequences of the Congo Basin deforestation on agriculture through an understanding of the effects of forest loss on rainfall and that of rainfall on agriculture. It is worth noting that deforestation cannot be directly linked to agriculture; the association must go through one or several intermediate processes. For instance, decrease in organic matter due to slash and burn deforestation could have negative impacts on agriculture. Here, we will mainly focus on the effects through rainfall as it remains a dominant factor for agricultural activities in Africa.

To get an overview of the causes of deforestation in the Congo Basin, the first section of this report focuses on the local context that leads to forest clearing in the Basin. This is then followed by a description of the observed pattern of Congo deforestation (§2). In §3, the physics behind the link between deforestation and rainfall is briefly described. Section 4 focuses on the roles of the Congo Basin as a moisture source or sink for the surrounding regions. The contribution of the Congo rainforest on local and regional rainfall is also discussed in this section. In §5 and §6, the impacts of deforestation on rainfall and agriculture are assessed. The report is concluded by an identification of a number of knowledge gaps and recommendations for further investigation, in order to improve the current understanding of the roles of the Congo Basin rainforest on climate and agriculture.

2. Socio-economic drivers of Congo Basin deforestation

There is still scholarly debate as to the socio-economic drivers of tropical deforestation in general and how these drivers change over time and space. Reviewing the causes of tropical deforestation using 152 subnational cases, Geist and Lambin (2002) identify institutional governance factors as the main culprits. Contreras-Hermosilla (2000), rather identifies interrelated actions by a number of agents as the main causes of forest changes, while Sengupta and Maginnis (2005) distinguish between proximate and underlying causes. Proximate causes include agricultural expansion, infrastructure development, wood extraction, forest fires, alien invasive species, and climate change. Underlying causes include market failure, institutional and governance policies, demographic factors, and poverty.

Palo (1994) reflected on the neo-Malthusian tradition among biologists and ecologists to consider the causality of population pressure on deforestation. Noting that a fundamental feature of excess deforestation is that the causal factors are linked together as various parts of a chain, Palo undertook multiple regression analysis of 60 tropical countries to find that population pressure was related to the extent of forest cover.[1] Repetto and Holmes (1983) argue that population growth, together with open-access, asymmetric land tenure and forest commercialization with increasing international demands, leads to faster deforestation than population growth alone. Barbier (1989) concludes that the socio-economic factors that induce households to expand populations can lead to cumulative and unsustainable demographic pressures on a fragile forest base. But others, notably Westoby (1978 and 1989) have criticised the notion that population pressure should be seen as an underlying cause of tropical deforestation, arguing that inequality and poverty are more important. Other socio-economic drivers discussed in the literature include the structuring of international debt payments (Khan and McDonald 1994) and the low market valuation of forest carbon sinks.

While there is still debate as to the underlying preconditions that lead to deforestation and forest degradation, the proximate drivers of contemporary tropical forest loss have become clearer thanks to satellite data and other techniques. Using high-resolution Google Earth imagery to map and classify global forest loss since 2001, Curtis et al. (2018) found various factors to be immediate drivers: commodity production, forestry activity, agriculture, wildfires, and urbanisation. In large parts of Africa, Curtis et al. (2018) note that forests are typically cleared to make space for subsistence agriculture or to produce fuelwood.

In the Congo Basin, data and analysis from Global Forest Watch at the University of Maryland (GFW hereafter) shows that, from 2000 to 2020, the largest percentage decrease in tree cover loss was seen in the DRC (9.2%), followed by Cameroon (5.9%), Equatorial Guinea (5.2%), and Republic of Congo (3.7%). Gabon and CAR both saw the equivalent of a 2% decrease in their tree cover during the same period. The total decrease in tree cover from 2001-2022 in all Congo Basin countries is estimated to be in the region of 22.8 Mha using GFW data. It should be noted, however, that GFW changed its estimation method in 2015, so comparisons that span across this year should be treated with caution. Caution is particularly required for Central Africa, given that the new GFW methods employed since 2015 are more sensitive to relatively small-scale deforestation, as typically seen in the Congo Basin as opposed to Southeast Asia. Indeed, in all Congo Basin countries, shifting agriculture was identified as the dominant proximate driver of tree cover loss in each of the years 2001 to 2022. However, in DRC, for example, other recent proximate drivers were forestry activity and urbanisation. A summary of country level data is provided in Table 1 (next page).

[1] Malthus (1766-1834) argued that over-population created and exacerbated poverty, and that restricting births was a means to achieve economic security (Klausen and Bashford, 2010). Neo-Malthusianism is a term used in the literature to describe a particular emphasis on population pressure as a cause of deforestation. The relative importance of population in driving deforestation is still subject to much scholarly debate.

Table 1: Overview of Congo Basin Tree Cover and Deforestation, 2000–2022. Source: Global Forest Watch, 2023. *Reflects available GFW data.

	Ha. of tree cover by type, 2000*	**% Decrease in Forest Area, 2001-2022 (ha)**	**Co2e from forest loss, 2001-2022**	**Dominant deforestation driver**	**Top three subnational regions for forest loss**
Cameroon	31.4 Mha natural forest, 100 kha plantations, 15.1 Mha other	5.9% (1.84 Mha)	1.09 Gt	Shifting agriculture	Center, Est, Sud
Central African Republic	47.1 Mha tree cover, 14.9 Mha other	2% (961 kha)	450 Mt	Shifting agriculture	Mbomou, Ouham, Ouham-Pendé
Democratic Rep. of Congo	199 Mha natural forest, 170 kha plantations, 33.6 other	9.2% (18.4 Mha)	11.4 Gt	Shifting agriculture	Tshopo, Sankuru, Maniema
Equatorial Guinea	2.65 Mha tree cover, 41.3 kha other	5.2% (139 kha)	88.8 Mt	Shifting agriculture	Litoral, Centro Sur, Kié-Ntem
Gabon	24.7 Mha natural forest, 8.6 kha plantations, 1.76 Mha other	2% (506 kha)	313 Mt	Shifting agriculture	Ngounié, Haut-Ogooué, Wouleu-Ntem
Rep. of Congo	26.4 Mha tree cover, 7.78 Mha other	3.7% (968 kha)	573 Mt	Shifting agriculture	Pool, Likouala, Sangha

In their review of scientific narratives of deforestation drivers in the Congo Basin and Southeast Asia, Wong et al. (2022) concur with the GFW data. Smallholders practising shifting cultivation is routinely identified in studies as a proximate driver of deforestation and environmental degradation, exacerbated by population growth and migration, in both regions. But Wong et al. (2022) point out that other drivers in both the Congo Basin and Southeast Asia are increasingly identified in the scientific literature, including roads, commodity production, mining and illegal logging.

Tegegne et al. (2016), in their review of socio-economic drivers of deforestation and forest degradation in Cameroon and the Republic of Congo also note that most of their respondents[2] (75%) indicated subsistence farming, particularly slash and burn farming, as a currently (very) important proximate driver of forest loss in Cameroon. Close to 70% of the Cameroonian population was noted in this study to depend on farming activities for their livelihoods, contributing to 85% of the deforestation in the country (Molua, 2012). In Congo, 45% of Tegegne et al.'s (2016) respondents rated unsustainable agricultural expansion by smallholder farmers as an important current driver. The Republic of Congo was noted as only using close to 2% of its_arable land – also including secondary forests – while the country is a net annual food importer (Hourticq et al., 2013; Rakotoarisoa et al., 2011).

There is, however, significant debate in the literature surrounding the impact of shifting cultivation in the Congo Basin: while shifting cultivation has been targeted as one of the main proximate drivers of deforestation and forest degradation and an increase in swidden area in Cameroon has been reported (Sunderlin et al., 2000; van Vliet et al., 2012), some empirical case studies have argued that its adverse effect on forest cover and health is minimal (Geist and Lambin, 2002; Ickowitz, 2006).

Tegegne et al. (2016) also note that, in Cameroon and Republic of Congo, deforestation and forest degradation is driven not only by immediate, single-factor, causes, but by underlying institutional, demographic, economic, technological and cultural variables. The three most important indirect causes mentioned most often by their respondents: were (i) institutional and policy factors; (ii) demographic; and (iii) economic factors.

A high proportion of Tegegne et al.'s (2016) respondents (78% in Cameroon; 60% in Congo) noted that weak and overlapping legal frameworks, inconsistency and lack of coordination in formal state policies, particularly those related to agriculture, mining, industrial development and the energy sectors, constituted the most important group of institutional factors driving deforestation in both countries. Along the same lines, both countries score very low on the corruption perceptions index and on other governance indices. More than 50% of respondents from both countries associated corruption with deforestation, mostly due to unsustainable timber logging, non-transparent issuance of permits, and concessions. In Cameroon, Cerutti and Lescuyer (2011) reported several incidents of non-transparent allocation of titles influenced by corrupt public officials who have personal interest in the companies involved in the process.

The most frequently mentioned demographic driver in Cameroon in Tegegne et al. (2016) was population growth (72%). Pressure on the forest resource is growing because the country's annual population growth rate is 2.6% (Cameroon, 2013). Congo's population growth rate is even higher at 3.2% (MDDEFE, 2011). Aside from overall population pressure (55%), the most cited demographic

[2] Respondents were 50 national-level experts in forest and land use policy in Cameroon and the Republic of Congo.

factors in Congo were uneven spatial population distribution (65%) and in-migration (45%). About 60% of the population live in the five main cities, while most of the population is still reliant on exploiting the forest for their subsistence livelihoods.

The key economic factors causing deforestation and forest degradation in Cameroon and Congo are overall market/demand growth and commercialisation (54% in Cameroon; 60% in Congo), specific economic structures (75% in Cameroon; 50% in Congo), and the associated intensified pressures on natural resources. Market growth is affecting forests in both countries mainly due to commercial logging and industrialisation and expansion of agriculture. The market demand for forest resources is dominating because of intensified commercialisation of the wood market.

A high proportion of Tegegne et al.'s (2016) respondents acknowledged that the expansion of agro-industrial plantations (90% in Cameroon; 80% in Congo) and mining operations in forested areas (40% in Cameroon; 50% in Congo) could lead to drastic deforestation impacts in the coming years. Many factors – e.g., investment proposals in the agricultural sector – support such expectations. Confirmed and potential future expansion of oil palm and biofuel plantations are estimated, for example, at 640,000 hectares (ha) in Congo and 1060,000 ha in Cameroon, especially in forested and formerly forested land (The Rainforest Foundation UK, 2013). The Congo Basin is attractive for oil palm plantations because land availability for oil palm plantations is diminishing in Malaysia and Indonesia and approximately two-thirds of the total forest area of the Congo Basin has suitable soil and climate for growing oil palms, which is a native species (The Rainforest Foundation UK, 2013).

In the DRC, Samndong et al. (2018) found that contextual factors influence household decisions to clear forest. They observed that households in Equateur Province were more likely to clear forests when they had experienced recent economic shocks. In the study area, with limited alternative livelihood activities, forest clearing to boost agricultural output was a coping strategy. Households that lived further from the forest were less likely to clear forest compared to those that are close. In addition, commercialization of agricultural products increased the likelihood for forest clearing. The presence of logging activity from 2008 to 2013 significantly affected household decisions to clear forest and the effect was substantial. Importantly, the presence of state rules (effective regulation) seemed to be effective in reducing local people's likelihood to clear forest in general.

In summary, available studies and data show various underlying and proximate drivers contributing to ongoing deforestation in the Congo Basin, with all countries experiencing (to varying degrees) net forest loss between 2000 and 2020. Since 2015, after which GFW have used a similar method with minimal changes, forest loss appears to have been relatively stable in the Democratic Republic of Congo, Republic of Congo, Equatorial Guinea, and Gabon, while appearing to increase in the Central African Republic and Cameroon. Several studies project that rates of forest loss in the Congo Basin will increase in the coming years and decades.

3. Observed deforestation patterns

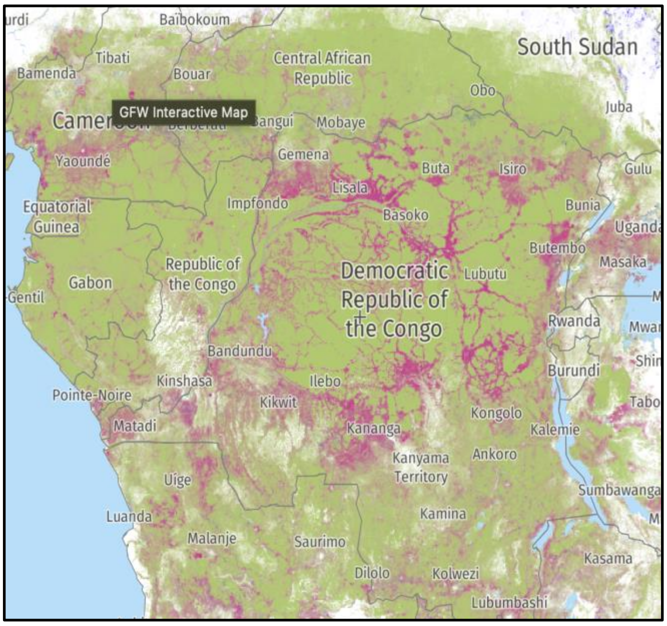

Fig. 1: Congo Basin Tree Cover Loss, 2001-2022 (Pink indicates lost tree cover >30% canopy density). Source: Global Forest Watch, University of Maryland, 2023.

Figure 1 shows the estimated tree cover loss during the last few decades. Aquilas et al. (2022) note that the forest area in the Democratic Republic of Congo (DRC) is higher relative to other countries in the region – though the trend is declining. The value fell progressively from about 147 million hectares in 1996 to 137 million hectares in 2020, averaging about 138 million hectares between 1996 and 2020. According to Global Forest Watch, the DRC lost 5.32 million hectares of humid primary forest between 2002 and 2020 and 15.9 million hectares of tree cover between 2001 and 2020. Apart from Equatorial Guinea with an average forest area of approximately 3 million hectares between 1996 and 2020, the average forest area cover was about 21 million hectares for Cameroon, 23 million hectares for Central African Republic (CAR), 22 million hectares for Congo and 24 million hectares for Gabon. Aquilas et al. (2022) claim that the general trend in forest area is linear and deterministic, marked by a continuous increased deforestation (reduction in forest area) in the Congo Basin.

Ernst et al. (2013) mapped the spatial distribution of deforestation, reforestation, degradation and regeneration processes in the Congo Basin. They found that the region around Gemena (around 3°N–20°E), and Lisala (around 2°S–22°E) at the forest fringe, in Northern DRC, experienced a high forest cover change process between 1990 and 2005. They observed forest fragmentation along the road network and noted that the region is under pressure due to its rising population, food crop production and industrial plantations. The transportation system is well developed around Lisala with river and road networks, which allows for the provision of agricultural products to Brazzaville and Kinshasa.

Ernst et al. (2013) also found that the forests of the southern of DRC, around Kananga (around 5°S–23°E) and to the East of Kindu (around 5°S–27°E), also exhibited high rates of deforestation and forest degradation between 1990 and 2005. These regions are important mining centres, and there is a direct pressure on forest cover by ore exploitation and by agriculture expansion around the mining centres.

Ernst et al. (2013) noted that the Eastern DRC is among the most populated areas of the country and is characterised by high deforestation and degradation rates in 1990–2000 and 2000–2005 with hot spots at Beni (around 0°N–30°E) and Bukavu (around 2.5°S–28.5°E). This civil unrest area was very degraded because of armed conflict, ongoing deforestation, agricultural encroachment, illegal hunting, and fishing and mining. The presence of refugee camps also accelerated the deforestation process near Virunga Park.

In Cameroon, Ernst et al. (2013) only identified hot spots in the east and the southwest regions for the 1990–2000 epoch as there was a clear lack of data between 2000 and 2005. After the 1986 economic stagnation, deforestation increased due to rural population growth and a shift from tree to food crops. In 1994, the devaluation of the CFA franc stimulated timber exports and led to greater forest degradation.

Ernst et al. (2013) found, too, that regions with high deforestation rates in the 1990–2000 epoch also experienced high deforestation rates in the second epoch. This was, for example, the case for Gemena and Lisala regions (DRC) and south of Owando (Congo around 0.5°S–16°E). They also observed a spatial extension of deforestation process in 2000–2005 to new regions such as Buta (around 3°N–25°E), Kisangani (around 0.5°N–25°E) and the Mbandaka-Basankusu axis, in the central part of the Cuvette (DRC).

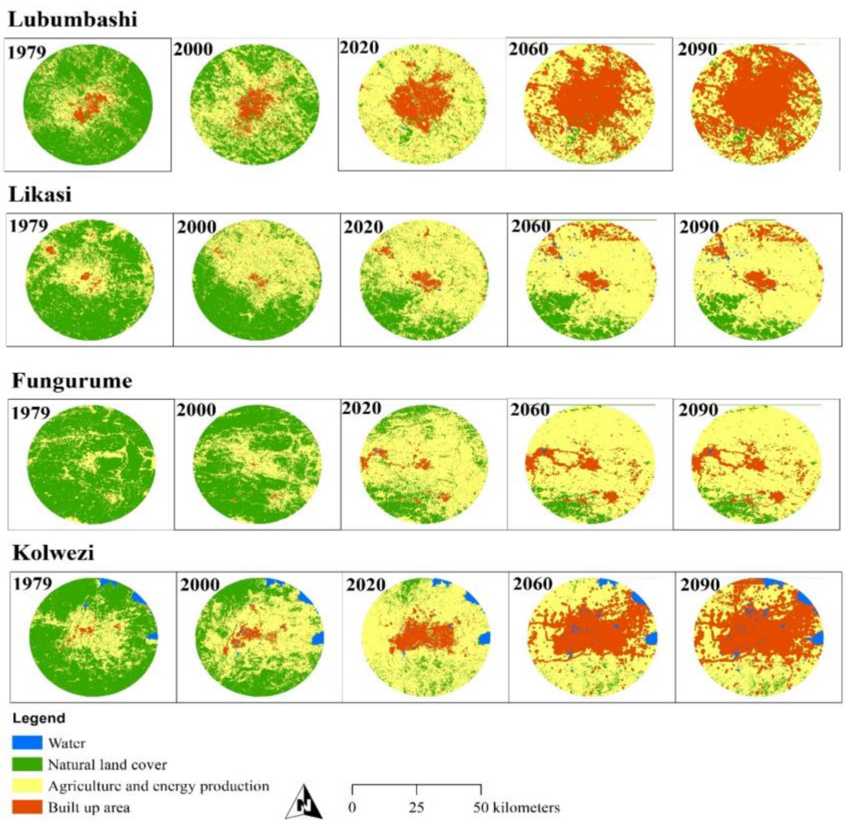

Fig. 2: Quantification and Simulation of Landscape Anthropisation around the Mining Agglomerations of South-eastern Katanga (DR Congo) between 1979 and 2090. Source: Muteya et al. (2022)

Muteya et al. (2022) consider land use changes in South-eastern Katanga (DRC) resulting from mining, also projecting likely trends by the years 2060 and 2075. They find that the natural cover that dominated the landscape in 1979 lost more than 60% of its area in 41 years (1979–2020) in favour of agricultural and energy production, the new landscape matrix in 2020, but also built-up areas. These disturbances, amplified between 2010 and 2020, were more significant around

Lubumbashi and Kolwezi. Muteya et al. (2022) project that built-up areas which spread progressively will become the dominant process by 2060 in Lubumbashi and by 2075 in Kolwezi (Fig. 2).

Céspedes et al. (2023) addressed the temporal effects of the Covid-19 pandemic on tropical deforestation. They found that deforestation in Africa rose slightly above the expected trend for the year 2020, suggesting that some pandemic-related factors and restrictions may have influenced forest cover changes in the region. Across Sub-Saharan Africa, biomass burning emissions increased during the COVID-19 lockdown period, resulting mostly from the burning of forests, shrublands and cultivated lands. This increase in fires to meteorological and vegetation conditions that may have favoured the spread of fires from agricultural activities and to the closure of wildfire management and control agencies during the lockdown periods. It is possible that local-scale forest cover loss resulting from an increase in fires in 2020 is underrepresented in Céspedes et al. (2023) given the 250 m spatial resolution of the Terra-i system. Furthermore, they note that deforestation in tropical Africa historically has been driven by small-scale shifting agriculture and wood energy demands, which also may be underrepresented at this resolution.

Céspedes et al. (2023) note that the effects of the pandemic on deforestation in the region may be prolonged given that economic recovery in Sub-Saharan Africa is expected to be slow. The International Monetary Fund (IMF) predicted the region would have the world's slowest economic growth in 2021, with per capita GDP in many of the region's countries not returning to pre-crisis levels until late 2025. Notably, post-pandemic economic recovery in the DRC was noted likely to rely heavily on the mining sector, as its economy is driven mainly by the extraction of mineral resources. As of 2019, the sale of mining and hydrocarbon products abroad accounted for more than 90% of the country's export revenues. Government rollbacks on environmental safeguards in the DRC in July 2020 were introduced to facilitate large-scale mining.

4. Physical mechanisms

Deforestation corresponds to the removal of deep-rooted trees, typically to be replaced with agricultural land on which grasses, shrubs and crops are physically smaller than trees, have a lower density of leaves, and have shallower roots. These changes lead to several effects on the physical climate system, including the winds, temperatures, humidity, and the way in which these vary over time. Those changes then alter patterns of rainfall both over the "local" region (the region which has been deforested, and the neighbouring forests which remain) and over remote regions. We can summarise the physics of these effects as follows (see review by Spracklen et al., 2018).

When plants are active and well supplied with water, they carry moisture from the soil to the air through their leaves, and most of the sun's energy arriving at the surface is used up in this process of *evapotranspiration*[3]. One measure of the ability of plants to drive evapotranspiration is the density of leaves over the land, measured by leaf area index (LAI)[4]. Trees generally have a higher LAI than smaller plants, and so there is usually higher evapotranspiration over forests than over deforested land. The deep roots of mature trees also take water from deeper levels of the soil, which grass and agricultural land cannot access. As a result, evapotranspiration over forested regions is

[3] *Evapotranspiration* is a combined term encapsulating loss of soil water both by evaporation from the soil surface and by transpiration from the leaves of the plants growing on it.

[4] The *Leaf Area Index (LAI)* is the surface area of leaves per unit surface area of the land.

more strongly maintained in dry periods than it is over deforested areas, when the upper levels of soil become dry and shallow-rooted plants can no longer transpire. Indeed, Luo at al. (2022) indicated that the rainy season over the Congo and neighbouring regions becomes shorter following deforestation.

The air over deforested areas is drier than air over neighbouring forest, and it is also warmer, because the sun's energy goes into heating the land and air, rather than into evaporating water.

There is a secondary effect on temperature and humidity, namely that deforested areas tend to be "brighter" than the remaining forest. The increased *albedo*[5] means that the deforested area absorbs less of the sun's energy. This tends to cool the deforested surface, but the effect is smaller than that of reduced evapotranspiration, and the net effect is still typically warming and drying over the deforested region. However, in an extreme scenario of high levels of deforestation on the continental scale, it has been suggested that the albedo effect could lead to total loss of the forest, even resulting in desertification on the poleward margins (Charney et al., 1975).

Deforested areas, with smaller plants, also have lower *roughness*[6] than the forests which they replace. This change leads to an increase in the winds in the low levels of the atmosphere. Over areas where the rainfall is already driven by wind circulations, for instance rains associated with a coastal *sea breeze* (Crook et al. 2022), or, probably, lake- and mountain- winds, deforestation can accelerate those circulations and change the rainfall patterns (for instance move the rainfall further inland). However, these effects are probably not large on the continental scale.

The general response of rainfall to the response in temperature, humidity and wind is more complicated, because there are feedback mechanisms between all these parameters. The response depends on the spatial scale considered.

On the local scale of around 10–100 km there is evidence from observations and models (e.g., Garcia-Carreras et al. 2011) of increased rainfall over the deforested area and reduced rainfall over adjacent forest. Although air over the deforested area is drier, moisture is supplied by winds from adjacent forest, and the hot air over deforested land rises and triggers clouds. Locally, this increase in rainfall probably mitigates the drying that is caused directly by deforestation, but reduction of rain on the remaining forest is a concern, since it may exacerbate the approach of the forest to the critical amounts of rainfall for survival of trees.

Taylor et al. (2022) have shown that urbanisation (replacement of vegetated areas with urban areas) can lead to increased risk of severe storms, with corresponding flood and landslide hazards.

On the continental scale, widespread deforestation reduces the average evapotranspiration over the area, and this is seen in climate models to be associated with a reduction in average rainfall over the continent (e.g., Bell et al. 2015; Smith et al. 2023). The physical mechanisms that resupply moisture to a deforested region on the local scale cannot operate effectively over larger distances

[5] *Albedo* is a measure of the reflective properties of a surface. Bright surfaces reflect more of the incoming solar radiation than dark surfaces.
[6] *Roughness* is a measure of the friction between the surface and the air.

(greater than around 200 km), and rainfall is seen to be reduced according to the reduction in available moisture from the surface.

On the continental scale, rainfall is also influenced through feedback mechanisms with winds and circulation. Rainfall over a region generally comes from three main moisture sources: moisture transported by the atmosphere from remote areas, local evapotranspiration and water vapour that is already in the atmosphere. Quantitative evidence of these processes is presented in the following section.

5. The Congo Basin as a source and sink of moisture

Before we address the impacts of deforestation on rainfall, we provide an overview of the moisture budget of the Congo Basin. The first part of this section is a summary of the relevant literature on this subject, and the second part is a quantitative analysis based on state-of-the-art atmospheric data.

The roles of the Congo Basin rainforest on local and regional rainfall are discussed through an assessment of the moisture recycling ratio, defined as the amount of rain formed as a result of the rainforest's evapotranspiration.

Modelling studies, through tracking of the different paths of moisture parcels, have commonly been used to identify the sources of moisture for the Congo Basin. Overall, there is a large discrepancy between the findings in the existing studies over the Basin, depending on the tracking method, the delimitation of the Basin area, and the data used for the analyses. There are some differences between the results offered by different models (e.g., Luo et al., 2022) and there is evidence that models may underestimate the deforestation impacts (Baker and Spracklen, 2022).

By examining the relative contribution of evapotranspiration to moisture in the free troposphere, Worden et al. (2021) showed that evapotranspiration within the Congo Basin contributes 75%–85% of the annual rainfall in the Basin, in contrast to 50%–62% in the Amazon Basin. They therefore argued that loss of forest due to land use will likely have a greater impact on rainfall in Congo than in the Amazon. In the same study, the maximum evapotranspiration contribution to the atmosphere is found during the transition months (December–February and June–August), suggesting that the Congo rainforest could be an important source of moisture for initiating the rainy season. Given that 83% of the atmospheric moisture comes from evapotranspiration in February (before the first rainy season), a substantial reduction in rainforest could impact both the onset and amount of rain during the March–May season.

Figure 3 shows the contribution of the different sources of moisture to annual rainfall in the Congo Basin from a recent study by te Wierik et al. (2022). Overall, a significant part of the continental rainfall is vegetation-sourced. For the Congo Basin watershed, 52% of the annual rain is from local evapotranspiration. During dry seasons, when oceanic sourced moisture convergence is low, the local vegetation maintains the rainfall within the Basin, whereas from September to November (the second rainy season), the local contribution to rainfall is slightly reduced. These results are in agreement with that of Smith et al. (2023), showing that evapotranspiration contributes up to 50% of the total rainfall in the Congo Basin.

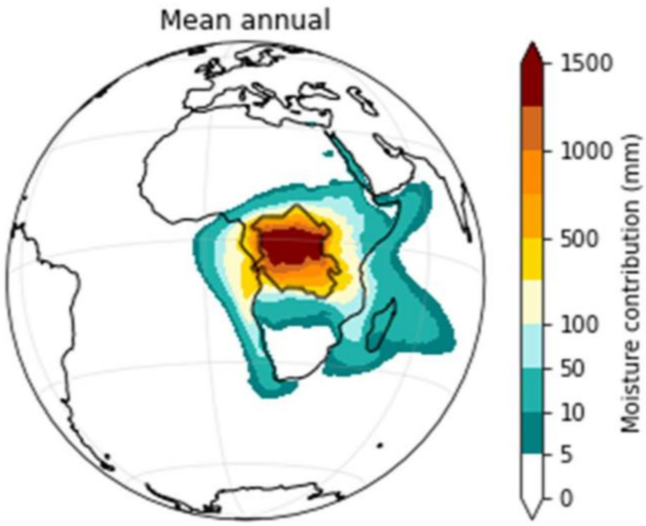

Fig. 3: Rainfall contribution from the moisture source regions over the Congo watershed. Figure taken from te Wierik et al. (2022).

Dyer et al. (2017) found a recycling ratio of 24–38% of the annual rainfall in the Congo Basin (Fig. 4). A much higher contribution of the Congo Basin was estimated by Sori et al. (2017), with 68% of the local rainfall identified to result from Congo rainforest evapotranspiration. This is further supported by a subsequent study (Sorí et al., 2022) in which moisture recycling in the area brings more than 60% of the annual rainfall. Other sources such as the Indian and tropical Atlantic Oceans, as well as eastern Africa, were also identified but with weaker contribution. During wet (dry) years, moisture contribution from the Congo Basin is higher (lower). Tuinenburg et al. (2020), on the other hand, showed that local evapotranspiration is responsible for 47% of the Basin's annual rainfall.

Although there is a large discrepancy between the results on the evapotranspiration's contribution to annual rainfall within the Basin (25% in Dyer et al., 2017; 85% in Worden et al., 2021), most studies agree that local evapotranspiration plays a dominant role (more than 50%) compared to other land or ocean sourced moisture.

Apart from the impacts of the rainforest on local rainfall, Spracklen et al. (2012) showed that air masses exposed to vegetation are moister and produce more rain, bringing at least twice as much rain as air passing over limited vegetation. This is particularly observed in air masses passing through the Congo Basin rainforest and transported to East Africa (Spracklen et al., 2012). During the June–August East African rainfall season, air masses originating from the Gulf of Guinea and southwestern Indian Ocean are moisture-loaded by passing through the Congo rainforest and contribute about 47% of the total moisture released over the Ethiopian highlands (Viste et al., 2011). Salih et al. (2015) also found that 22% of the Sahelian Sudan air mass, accounting for 40% of the annual rainfall, comes from the Congo Basin. By introducing the concept of "precipitationshed", defined as the upwind ocean and land surface that contributes evaporation to a specific location's rainfall, Keys et al. (2014) showed that the Congo Basin is one of the dominant moisture sources for the West Sahel region.

The remote effect of the moisture recycling over the Congo Basin is further supported by Dyer et al. (2017). By using a climate model which allows tagging water molecules, so that one can estimate where precipitated water originates. Figure 4 shows that a fairly large portion of the annual rainfall in South Sudan derives from the Congo Basin.

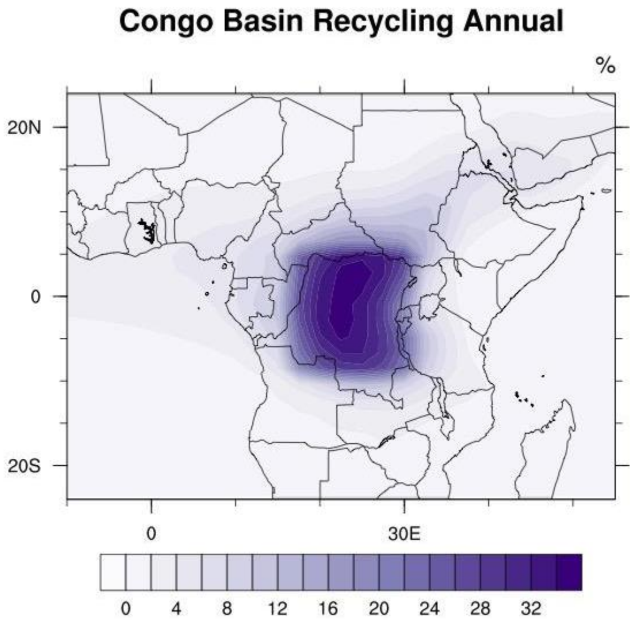

Fig. 4: Annual moisture recycling of the Congo Basin. The figure was kindly provided by Ellen Dyer. It corresponds to the seasonal maps in Fig. 6 in Dyer et al. (2017). The map shows the ratio of precipitation that comes from moisture evaporated in the Congo Basin to total precipitation.

By 2100, moisture recycling in the Congo Basin is projected to decline (Baker and Spracklen, 2022), due to large increases in moisture transported into the Basin, while the amount of evapotranspiration does not show a significant change.

We now establish a climatology of the total moisture coming into and going out of the Congo Basin throughout the year. The calculations were done using the ERA5 reanalysis dataset (Hersbach et al., 2020). ERA5 is a reconstruction of the three-dimensional atmosphere back to 1940, based on observational data including satellite imagery, and we downloaded monthly mean data for the period 1940–2022 (Hersbach et al., 2023) from the Copernicus Climate Data Store. We note here that reliable satellite data has only been available from around 1980, and this may have implications for the accuracy of the data prior to 1980.

The quantity that we computed is the total flow of moisture into or out of the Congo Basin, from the ground to the top of the atmosphere. In ERA5, this quantity is known as the *vertical integral of water vapour flux*. The unit is kilogrammes of water vapour per metre across the flow per second (kg m^{-1} s^{-1}). We transformed the numbers so that positive flux means that more moisture is coming into the Basin than what is going out. Similarly, negative values indicate a net export of moisture. We computed the mean moisture fluxes across four boundaries. Clockwise, these are: a northern boundary at 6°N and between 17°E and 29°E; an eastern boundary at 29°E and between 6°S and 6°N; a southern boundary at 6°S and between 17°E and 29°E; and a western boundary at 17°E and between 6°S and 6°N. We note that the areas of the boundaries are practically identical, since the northern and southern boundaries span 12 degrees at 6°N and 6°S, and the eastern and western boundaries span 12 degrees in the meridional direction.

In Table 2, the long-term averages of the moisture flux are listed, broken down on annual and seasonal aggregation levels. The first thing to note is that the mean annual moisture flux is positive, which means that (according to ERA5) the Congo Basin is a moisture sink. Annually, the incoming fluxes are 33% higher than the outgoing fluxes. The eastern boundary is the only boundary with a substantial positive flux, which means that East Africa (and the upstream Indian Ocean) is the main source of moisture. The outgoing fluxes through the western boundary correspond to 78% of the fluxes into the region through the eastern boundary, suggesting that the moist air masses largely pass over the Congo Basin, although they may interact with locally sourced moisture.

Table 2: Long-term (1940–2022) average incoming moisture flux through the four boundaries that define the Congo Basin reference region, averaged annually and for each of the four seasons: December–February (DJF); March–May (MAM), June–August (JJA); September–November (SON). The flux has a unit of kg m^{-1} s^{-1} and corresponds to the horizontal rate of flow of water vapour, per metre across the flow, for a column of air extending from the surface of the Earth to the top of the atmosphere. Positive values indicate a net flux into (and negative values out of) the Congo Basin.

	Season				
Orientation of fluxes	**Annual**	**DJF**	**MAM**	**JJA**	**SON**
Positive into the region from the north	3	32	1	–37	17
Positive into the region from the east	89	90	112	47	108
Positive into the region from the south	0	–39	19	27	–9
Positive into the region from the west	–69	–71	–105	–33	–67
Mean incoming flux	**5.8**	**3.2**	**6.7**	**1.2**	**12.2**

The seasonal cycle of the fluxes is also of interest. The largest incoming fluxes by far enter the region between September and November, which overlaps with one of the two main rainy seasons in East Africa, the ‘short rains’ (Palmer et al., 2023). In June–August, which is a generally dry period in East Africa (Palmer et al., 2023), the overall incoming flux is substantially lower: only about 10% of the flux in September–November. An outgoing flux from the Congo Basin into South Sudan at low levels during this time of the year is an important component of the rainy season in that region (Salih et al., 2015).

We also see that the ratio of outgoing fluxes through the western boundary to the incoming fluxes from the east follows a seasonal cycle. It is very high (94%) in the ‘long rains’ March–May season, the other of two main rainy seasons in large parts of East Africa (Palmer et al., 2023), but it is quite low (62%) in September–November. The reason is that there are substantial amounts of moisture coming into the Congo Basin from the west (the Atlantic) at low levels in March–May. This incoming moisture reduces the net total outgoing moisture through the western boundary.

Figure 5 is a schematic overview of how rainfall changes can be understood in relation to changes in the moisture sources due to patterns of Congo deforestation.

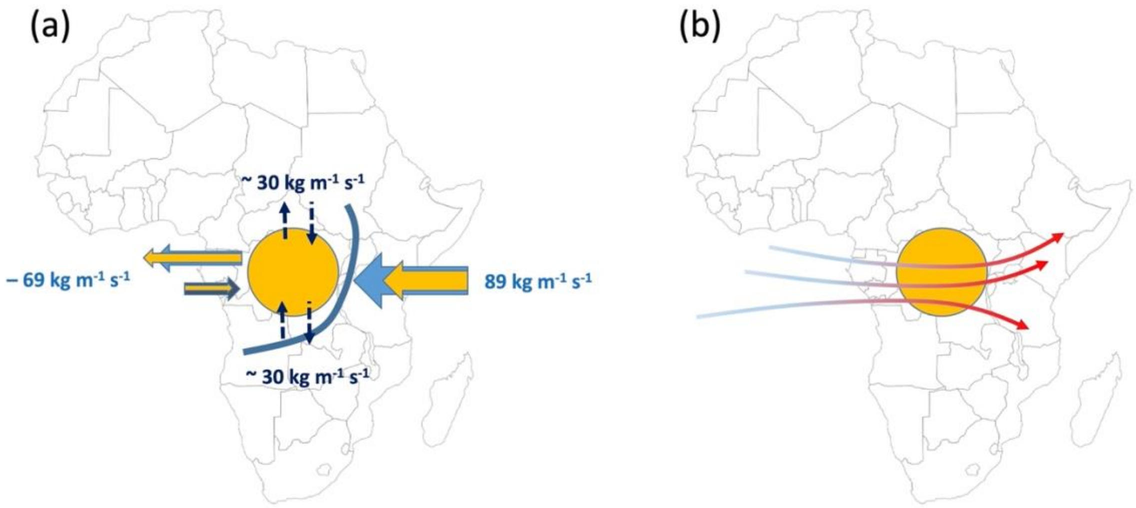

Fig. 5: A summary of the circulation changes and moisture flows associated with Congo Basin deforestation, consistent with results of Table 2 and Nogherotto et al. (2013). (a): Congo Basin deforestation is shown to reduce the moisture supply from the east and from the west. In the average climate state, the rain-bringing clouds over the Congo Basin cause a heating of the atmosphere; warm air rises and draws in moisture from the adjacent oceans in response (blue arrows to east and west, with net moisture fluxes as shown in Table 2; on the western side the low-level flow is inward (dark blue), and the upper-level flow is outward). A reduction in rainfall over the Congo Basin itself leads to a reduction in cloud-heating at higher altitudes over the Basin, and this in turn weakens the net moist inflow (yellow arrows, consistent with Nogherotto et al., 2013). These changes will influence the supply of moisture over wide areas of the continent. Dashed green arrows show the northern and southern moisture fluxes: as seen in Table 2, these have a small annual mean value, but they vary seasonally. (b): Air passing over deforested air is seen to have reduced opportunity to gain moisture from the underlying surface: this process has been shown in observations to reduce rainfall downwind of deforested land, in this case over East Africa.

Another aspect seen in Table 2 is the substantial variation in the fluxes from year to year. Figure 6 shows time series of the average annual incoming moisture flux values for the whole Congo Basin (the total flux through all the four boundaries defined above).

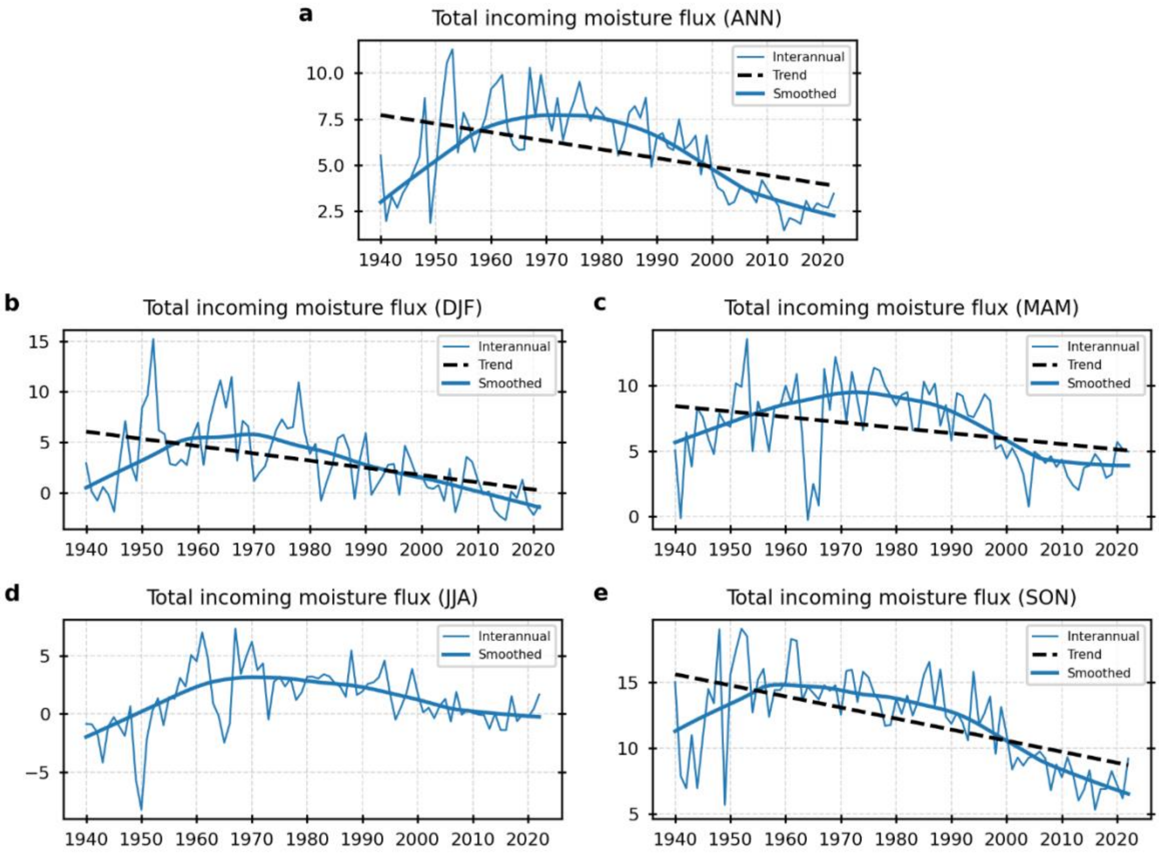

Fig. 6: Thin lines: Interannual time series for mean moisture fluxes annually (ANN, panel a), and during December–February (DJF, panel b, where the x-axis denotes the year of the December month), March–May (MAM, panel c), June–August (JJA, panel d), and September–November (SON, panel e). Thick lines: LOWESS-filtered time series. Dashed lines: linear trend (only shown when significant at the 5% level).

Although the available time series are too short to conclude with certainty whether the fluxes exhibit variability on the decadal time scale, we have added thick lines showing low-frequency-filtered time series (using a LOWESS filter; Cleveland, 1979) to Fig. 6. The annual mean fluxes in Fig. 6a show clear indications of multidecadal variability. There is also a clear overall decreasing trend of about 6% on average per decade. Negative trends are significant in all seasons except June–August.

Although not shown here, we have also calculated the trends in annual moisture flux for each of the four boundaries individually. There has been a strong increase of incoming fluxes of 2.7 kg m^{-1} s^{-1} per decade across the eastern boundary (from East Africa) and a weaker decrease (–0.4 kg m^{-1} s^{-1} per decade) of incoming fluxes through the northern boundary. At the same time there has been a very strong increase in the outgoing fluxes (3.8 kg m^{-1} s^{-1} per decade) across the western boundary (towards the Atlantic). This means that the main cause of the downward trend is a strong increase in the net loss of moisture across the western boundary. This could be either due to an increase in moisture export or a decrease in moisture import from the Atlantic, or it could be due to a combination of these factors. We do not know if there is a direct link to deforestation.

Finally, we emphasize that these time-averaged patterns can hide the important effects of day-to-day variations in the moisture budget, which can be very strong in the tropics. For instance, a tropical cyclone in the Indian Ocean may cause major changes in the patterns of winds, and associated moisture fluxes, lasting for a few days and causing heavy rainfall (Finney et al., 2020), but these short-term effects will not be seen in the longer-term averages.

6. Rainfall responses to Congo deforestation

In general, tropical deforestation leads to reduced evapotranspiration and increase in surface temperatures, causing changes in the lower atmospheric circulation which increase rainfall in some regions and reduce elsewhere.

As mentioned earlier, air masses exposed to forest bring at least twice as much rain as air passing over grass or croplands (Spracklen et al., 2012), also see Fig. 3b. Figure 7 (Source: Spracklen et al., 2012) shows that (i) there is a significant positive correlation between the cumulative index for plant canopies (or Leaf Area Index - LAI) and rainfall around the Congo Basin for most months of the year, namely the eastern and south equatorial Africa (shaded areas in the figure); and (ii) rainfall is at least doubled when air trajectories pass over extensive vegetation (stippling). Since some air masses reaching the East and South equatorial Africa are moisture-loaded over the Basin, the Congo deforestation could lead to drier air that brings less moisture and less rainfall in these areas.

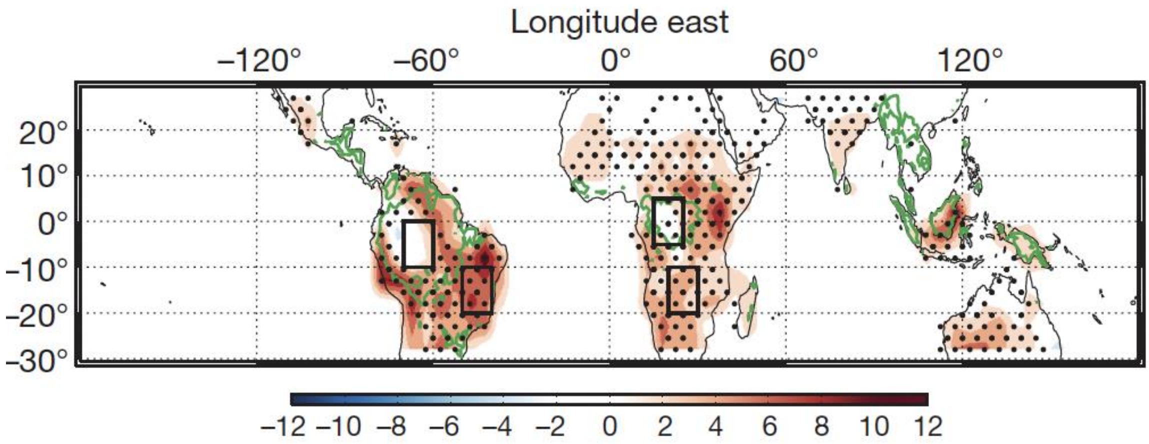

Fig. 7: Number of calendar months with significant correlation between rainfall and cumulative Leaf Area Index (shading). Stippling show areas where rainfall is at least doubled after the air trajectories pass through extensive vegetation (indicated by the black rectangles). Source: Spracklen et al. (2012)

By using radar-based forest disturbance information, Guo et al. (2022) found a significant negative correlation between forest disturbance and rainfall in the Congo Basin area. Smith et al. (2023), however, show that the rainfall response to deforestation is dependent on the size of the deforested area. Over the Congo Basin, clearing a forested area at a scale of 20 km leads to a significant increase in annual rainfall due to a moisture supply from the adjacent forest. If the scale is above 50 km, the annual and wet seasons' rains decrease while the dry season experiences an excess in rainfall. A complete deforestation of the Congo Basin is estimated to reduce the annual rainfall up to 10%–20% in the area. The rainfall responses outside the Basin are not investigated in these observational studies and the full impacts of the deforestation could be underestimated.

Sensitivity experiments with global and regional climate models have also been widely used to investigate the impacts of deforestation on rainfall. By artificially replacing all African forests with grasslands, Semazzi and Song (2001) found a significant depleted rainfall over the deforested areas, reaching up to 20% of the annual mean in the Congo Basin. The maximum rain deficit occurs during June-August (dry season), while a delay in the onset of both rainy seasons (February-April and September-November) are simulated. As shown by Worden et al. (2021), the contribution of evapotranspiration from the rainforest to the Congo Basin rainfall is highest during the transition or dry periods (December-February and June-August), acting as initiator of the rainy seasons. The results from Semazzi and Song (2001), agree well with the rainfall response to reduced evapotranspiration through deforestation. The length of the June-August dry season in the Congo Basin has been significantly decreasing since the 1980s (Jiang et al., 2019). It leads to an increase in the land evaporative demand, reduction in cloud cover and increase in surface incoming radiation, which in turns, amplifies aridity in the area. It would be important to understand the contribution of the moisture recycling in such a prolonged drying period.

A higher rainfall deficit, up to 50% of the annual average, associated with a significant warming of the surface temperature (2-4C) is found in Nogherotto et al. (2013) by completely removing the Congo Basin rainforest. Beyond the Basin itself, an increase in rainfall is depicted over the Sahel and some areas of the Ethiopian highlands, while the Guinea coast is characterised by rain depletion during June-September. These responses are due to an intensification of the West African Monsoon. During October-February, the north-westerly monsoon flow strengthens in response to removing the Congo rainforest, which in turn leads to an increase in rainfall over southern Equatorial Africa. A similar study was conducted by Bell et al. (2015) showing an increase of 2-3C in surface temperature by removing the Congo rainforest. The rainfall response, on the other hand, is characterised by a dipole anomaly pattern, with a decrease of 42% in the annual average rain over the western part of the Basin, and an increase of 10% in the east. The dipole pattern is mainly driven by the change in surface roughness after replacing the forest into grassland.

Lawrence and Vandecar (2015) conducted a pantropical deforestation study and found an increase of 0.5-2.5C in surface temperature and a decrease of 15% in annual rainfall by completely deforesting the Congo Basin. They, however, show that a more realistic scenario of deforestation yields less warming and less drying. They also suggest that there is a critical threshold beyond which rainfall is substantially reduced. Recently, a machine learning technique was used by Duku and Hein (2021) to investigate the impacts of deforestation on rainfall. By completely removing the Congo rainforest, a 50% decrease in annual rainfall is seen over Central Africa and South Sudan, while the Sudan-Sahel zone, Burkina Faso, southern Niger, Mali and northern Nigeria experience up to 40% of rain depletion. In addition, the timing of the peak rain over the deforested area is early and the duration of the rainy seasons is shortened. In contrast, the response to partial deforestation is location dependent. Over West Africa, higher tree loss in the Congo Basin leads to higher reduction in rain. In central and southern Africa, an increase in rainfall is depicted with a 50% tree cover loss while a threshold of 70% deforestation is needed for a robust rain reduction in these areas. Akkermans et al. (2014) also conducted a spatially explicit deforestation experiment instead of completely removing the forest and found a 2.6% decrease in rainfall over the Congo Basin. Changes in rainfall over coastal deforestation hotspots, such as the Republic of Congo, Gabon and Cameroon, are extended beyond the deforested areas, due to the shifts in the monsoon circulation and the deforestation-induced increase in moisture advection from remote areas.

A synthesis of the modelling studies on rainfall responses to deforestation in the Congo Basin shows that a complete replacement of the Congo rainforest into grassland leads to an overall decrease of 16% (+/– 17%) of the annual rainfall, similar to the impacts of a complete removal of the Amazon Forest (Spracklen et al., 2018).

Furthermore, the southern boundary of the Congo Basin rainforest forms the Congo-Air Boundary (CAB), a line where the humidity rapidly changes from very humid (Congo rainforest) to very dry (arid areas over Southern Africa) over a couple of hundreds of kilometres. From August to November each year, the CAB moves southward from the Congo Basin to southern Africa initiating the summer rains over the subcontinent (Howard and Washington, 2020), suggesting that the amount of available moisture from the Congo rainforest also impacts the rainfall onset over southern Africa.

In summary, these studies show that deforestation in the Congo Basin affects not only the mean rainfall in the Basin and neighbouring countries, but also the spatial distribution and the temporal characteristics of the rain, such as the onset, cessation and length of the rainy seasons. These have crucial implications in the agricultural sectors.

The projected Congo Basin forest loss between 2015 and 2100 is estimated to reduce the Basin's annual rainfall by 16.5 mm (+/– 6.2 mm), equivalent to a rainfall decline of 8%–10%. The Western Congo, where forest loss is projected to be highest, will experience the strongest rain depletion (Smith et al., 2023, Figure 8).

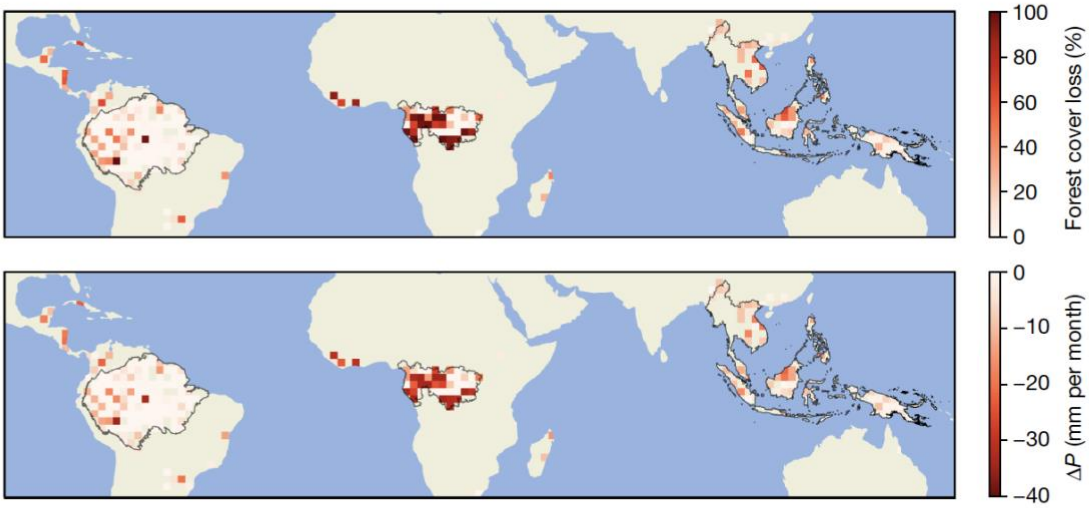

Fig. 8: Spatial pattern of projected forest cover loss over 2015-2100 under Shared Socioeconomic Pathway 3 (top); predicted change in rainfall (ΔP) in 2100 due to forest cover loss (bottom). Source: Smith et al. (2023)

7. Impacts on agriculture

There is no obvious direct link between deforestation and crop productivity. The association rather goes through one of several processes. Rainfall, which is influenced by deforestation, again influences soil moisture and soil quality. Deforestation will also have large effects on neighbouring regions as a result to its impact on rainfall patterns, which despite large uncertainties is believed to be potentially substantial. The indirect effect of deforestation on agriculture through the effect on rainfall is likely to be large, as there is a strong dependence on rain-fed agriculture in Africa.

A recent example is the five failed rainy seasons in East Africa between 2020 and 2022, leading to over 20 million people facing high levels of acute food insecurity due to failed crops and loss of livestock (ICPAC, 2022). Similarly, the March–May 2023 flood that followed the failed seasons swamped more than 1000 hectares of cropland, mostly affecting Ethiopia and Somalia. Although the mechanisms that drove these events are not fully understood, a possible role of the Congo Basin rainforest cannot be ruled out. The only conclusion we can confidently make is that there is a strong dependency on rainfall in the agricultural sector, so given the links between forest loss and rainfall patterns, linkages between deforestation and agriculture are likely.

Challinor et al. (2014) indicate that each percentage of rain depletion can trigger 0.5% decline in crop yields, while Smith et al. (2023) found that rainfall deficits due to a 10 percentage-point loss in forest cover can cause a reduction in crop yields by 1.25%. Based on these numbers, a complete deforestation of the Congo Basin, which is estimated to reduce rainfall by 16% (+/– 17%) (see previous section) could lead to a substantial decrease in crop yields not only in the Basin but also in the neighbouring countries. For instance, the estimated 50% decrease in rainfall in South Sudan by completely removing the Congo rainforest (Duku and Hein, 2021) could lead to a significant drop in crop production over the already semi-arid northern and south-eastern parts of the country, while the opposite could occur in the eastern Congo Basin where an increase by 10% in rainfall is estimated (Bell et al., 2015).

In addition to changes in the amount of rain, deforestation affects the spatial distribution of rainfall and its temporal characteristics. In a recent survey conducted in the NORCE-led EU project CONFER (*Co-production of Climate Services in East Africa*), there is a high demand from the agricultural sector for predictions of onset time, cessation time and length of the rainy season, as these parameters play as important a role as the amount of rain in determining the crop yields. Farmers rely on the knowledge of the rainfall timing to determine whether the soil has enough moisture to start the cropping season. Wakjira et al. (2021) found that an onset delay of five days could lead to 1.5% crop production losses over Ethiopia, while a 5-day shorter rainy season decreases the production by 1.1%. In a scenario of complete Congo deforestation, the start dates of the two rainfall seasons are delayed (Semazzi and Song, 2001) and the lengths of the rainy periods over Basin and neighbouring countries are shortened (Duku and Hein, 2021; Luo et al., 2022). These factors would very likely reduce the crop yields in the area.

8. Knowledge gaps

From assessing the existing literature on the impacts of the Congo Basin deforestation on climate and agriculture, and by comparing them with the studies conducted in the Amazon Basin, we identified the following gaps:

1) There are very few studies that directly link deforestation to crop yields in the Congo Basin and surrounding countries. It is therefore not feasible to specifically quantify the impacts of deforestation on agriculture in the area as it is in the Amazon. The numbers provided in §7 are for the global tropical regions and there could be some discrepancy for different locations, seasons, and crop types.

2) The impacts of deforestation on agriculture assessed here are solely based on the relationship between forest loss, rainfall availability and crop yields. A missing link is that of deforestation, soil quality and moisture, river runoff and crop yields, which could also play a non-negligible role.

3) There are large uncertainties associated with the impacts of the Congo Basin deforestation on local and regional rainfall:

- *Lack of observational data in the area*: In-situ, satellite and reanalysis datasets show opposite signs of changes in deforestation-induced rainfall (Smith et al., 2023). Such lack of data limits how climate models are evaluated, contributing to the large model divergence in the area (Washington et al., 2013).
- *Lack of understanding in the interaction between different mechanisms that drive rainfall for different seasons*: How large-scale atmospheric circulation interacts with local drivers such as the convection in the Congo Basin or orography, and how they modulate local and regional rainfall are still understudied. Deforestation changes the vertical profile of heating, effectively warming the low levels of the atmosphere and cooling aloft, and this has effects on the winds over large areas of surrounding land and ocean, which have not been well studied.
- *Lack of understanding in land-atmosphere interaction in the area*, which may partly lead to the persisting biases/errors in the models.

4) Although important, the deforestation tipping point beyond which the Congo Forest would stop functioning as a rainforest ecosystem has not been estimated, while it is established to be a clearance of 20%–25% of the forest in the Amazon (Lovejoy and Nobre, 2018).

5) Studies on the impacts of deforestation on convective storms and extreme rainfall events are missing in the Congo Basin, thus not included in the report. For instance, Taylor et al. (2022) found that deforestation (and in that case urbanisation) enhances extreme storms in West Africa, with associated risks to people and infrastructure. Whether deforestation partly influences the frequent intense mesoscale convective system in the Basin since 1999 is not understood and would need further investigation.

6) Although there is awareness that socio-economic drivers of deforestation in the Congo Basin are connected to each other, there is limited research on these relationships over time, including how they are impacted by various policy choices and interventions, such as family planning.

9. Recommendations

There is a crucial need for observational data, including rainfall, soil-moisture, and land cover in the Congo Basin area. These will help reduce the large uncertainties not only in the data themselves, but also in the models that are used to estimate the current and future impacts of deforestation. There is also a need for more detailed research on the relationships between drivers of deforestation in the Congo Basin over time and how these drivers are affected by policy choices.

A process-based understanding of the different mechanisms that drive rainfall variability, both in the Congo Basin and surrounding areas, is important to fully disentangle the possible role of the Congo rainforest on local and regional rainfall. The moisture fluxes examined in §5 provide a starting point for obtaining better insights, but an investigation of the atmospheric dynamics behind these fluxes has not been performed. A better understanding of the basic driving mechanisms could for instance yield more information on the causes of the increase in the length of the June–August dry season since the 1980s, which are not understood yet.

Most deforestation studies in the Basin have used idealized and/or exaggerated deforestation scenarios with relatively low-resolution climate models. Simulations using realistic historical deforestation with high-resolution climate models are recommended for a realistic and better representation of the small-scale mechanisms over the forest. Analyses of deforestation-driven storms will be feasible from such a model.

Within the CONFER project, a machine learning-based crop model has been developed to estimate the yields from rainfall availability and soil moisture. Similar techniques could be combined with the deforestation modelling studies to estimate the impacts of the deforestation on agriculture.

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